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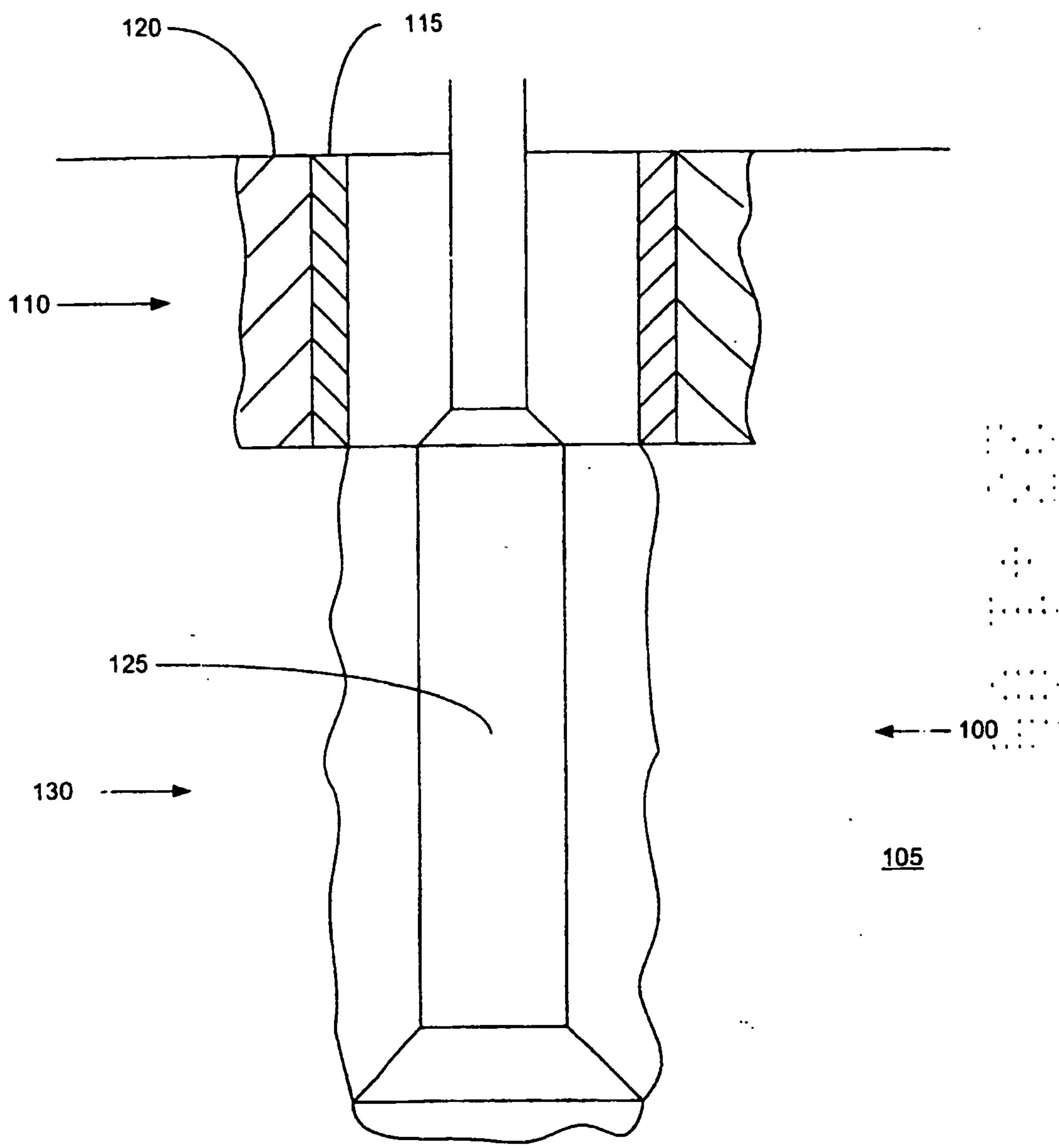

FIGURE 1

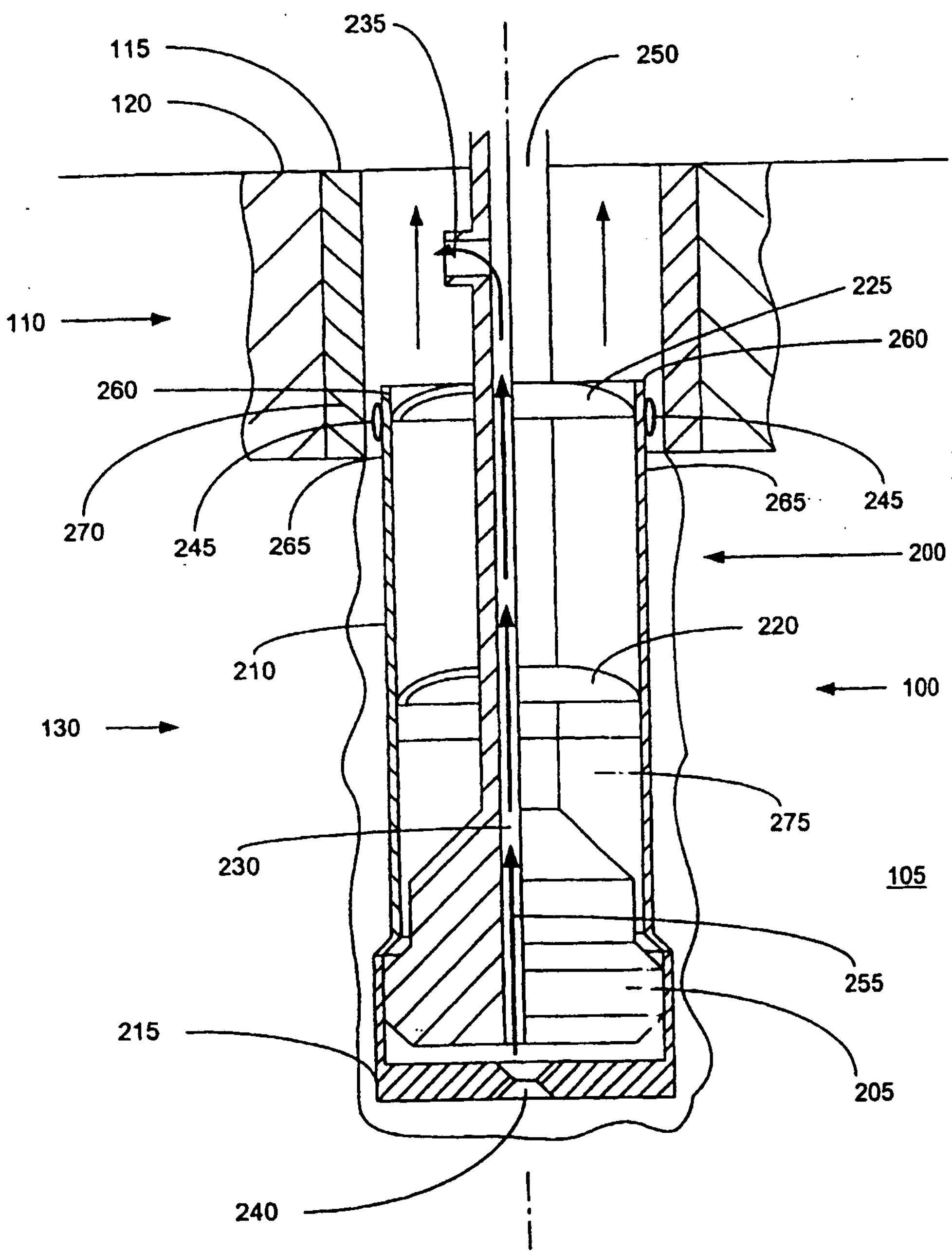
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FIGURE 2

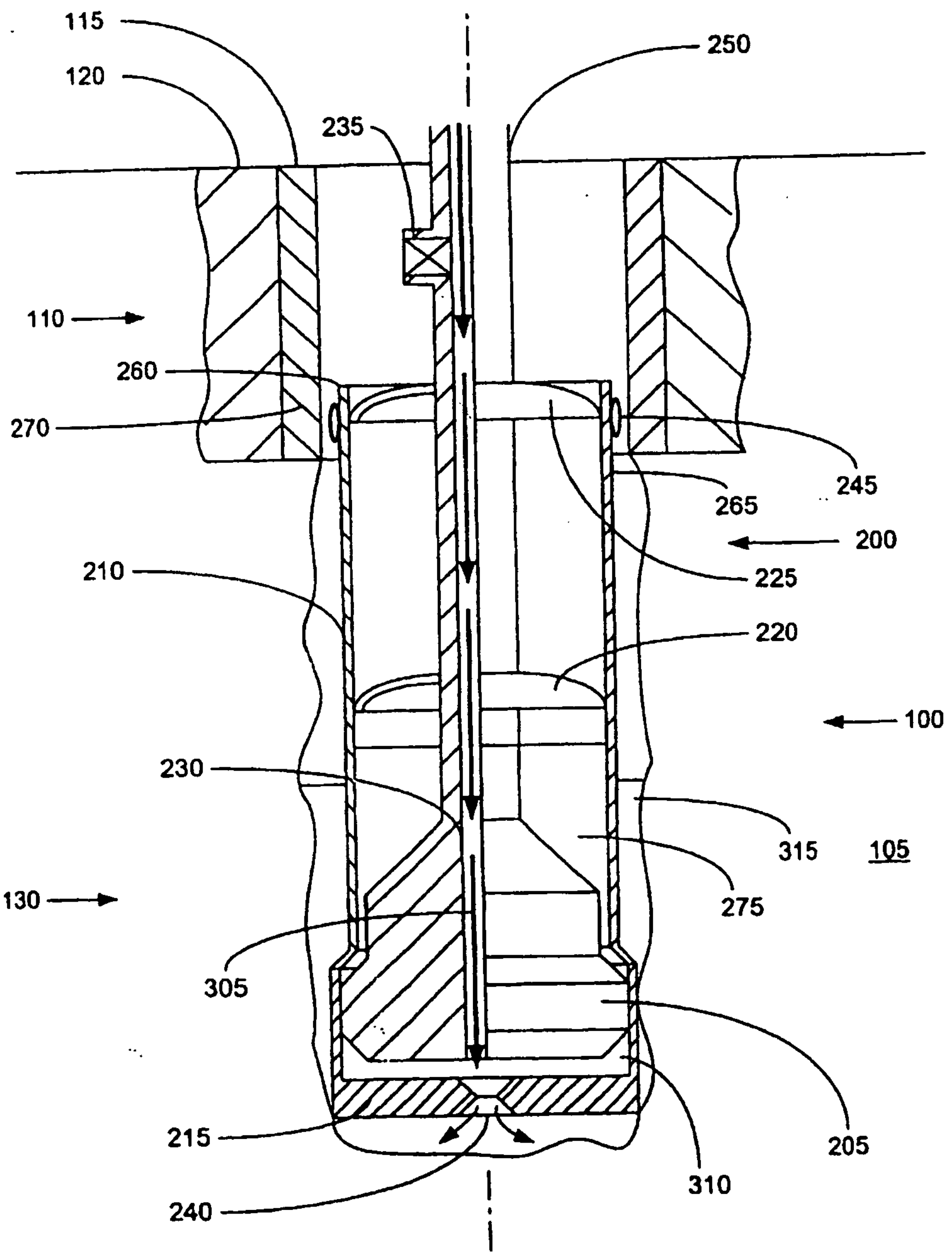
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FIGURE 3

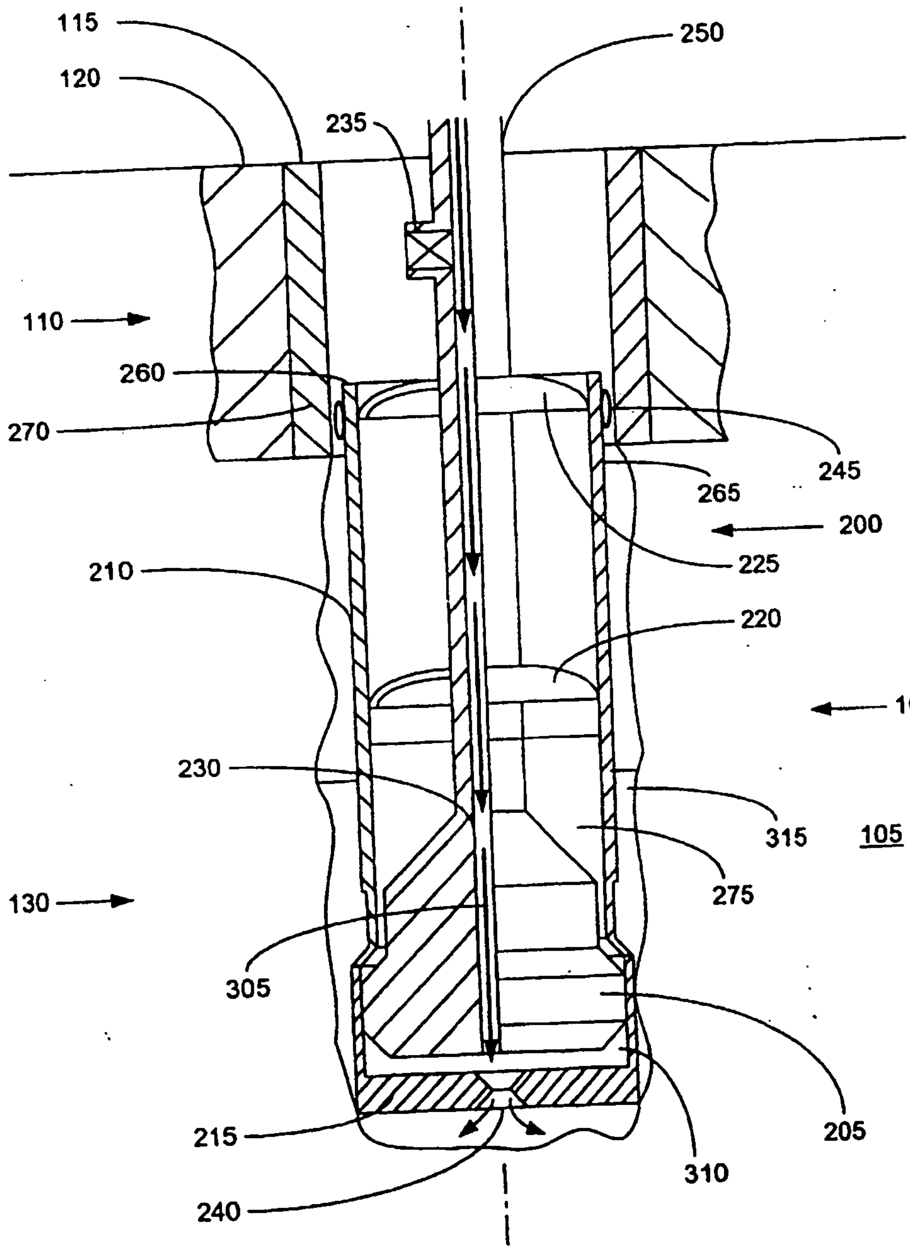
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FIGURE 3a

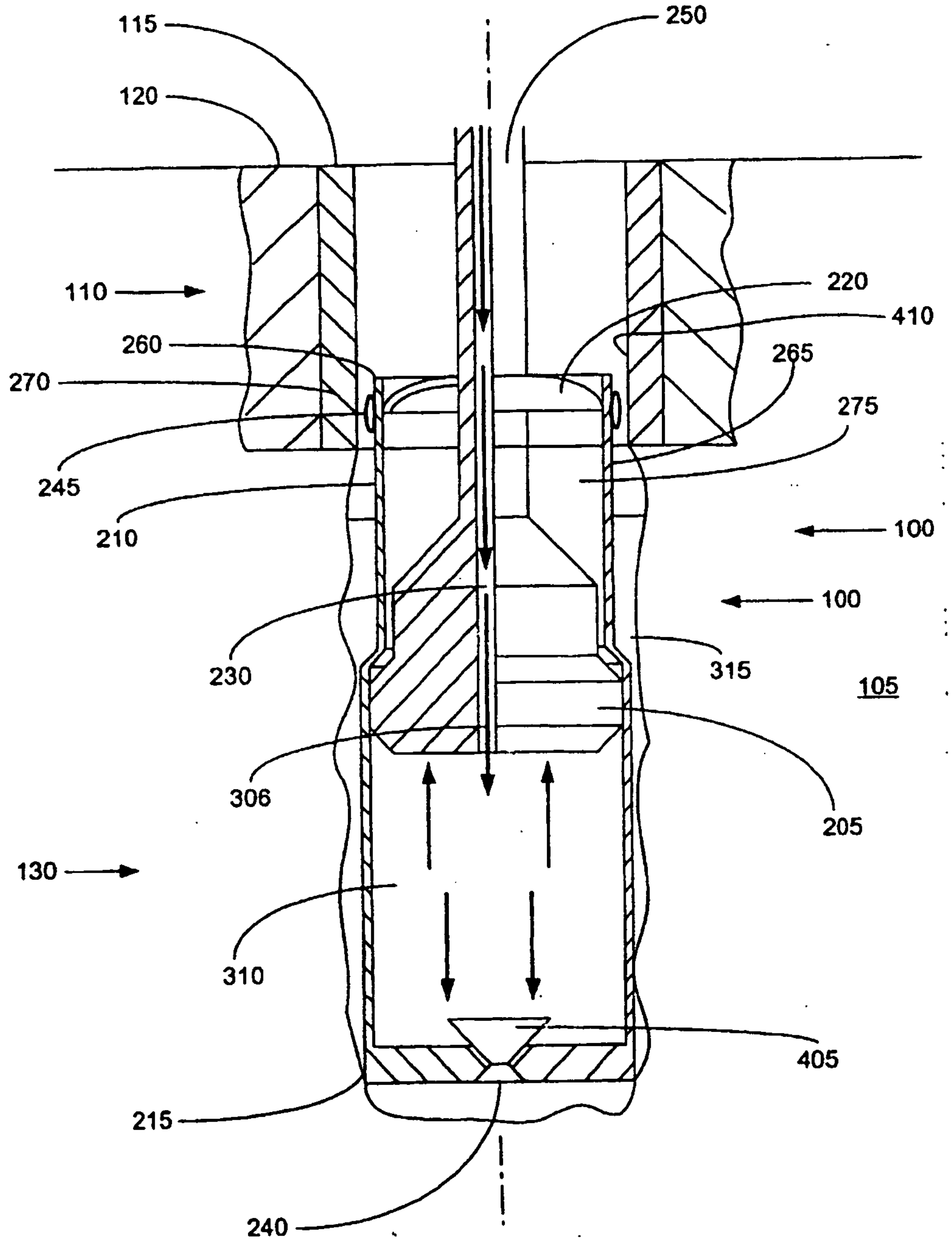
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FIGURE 4

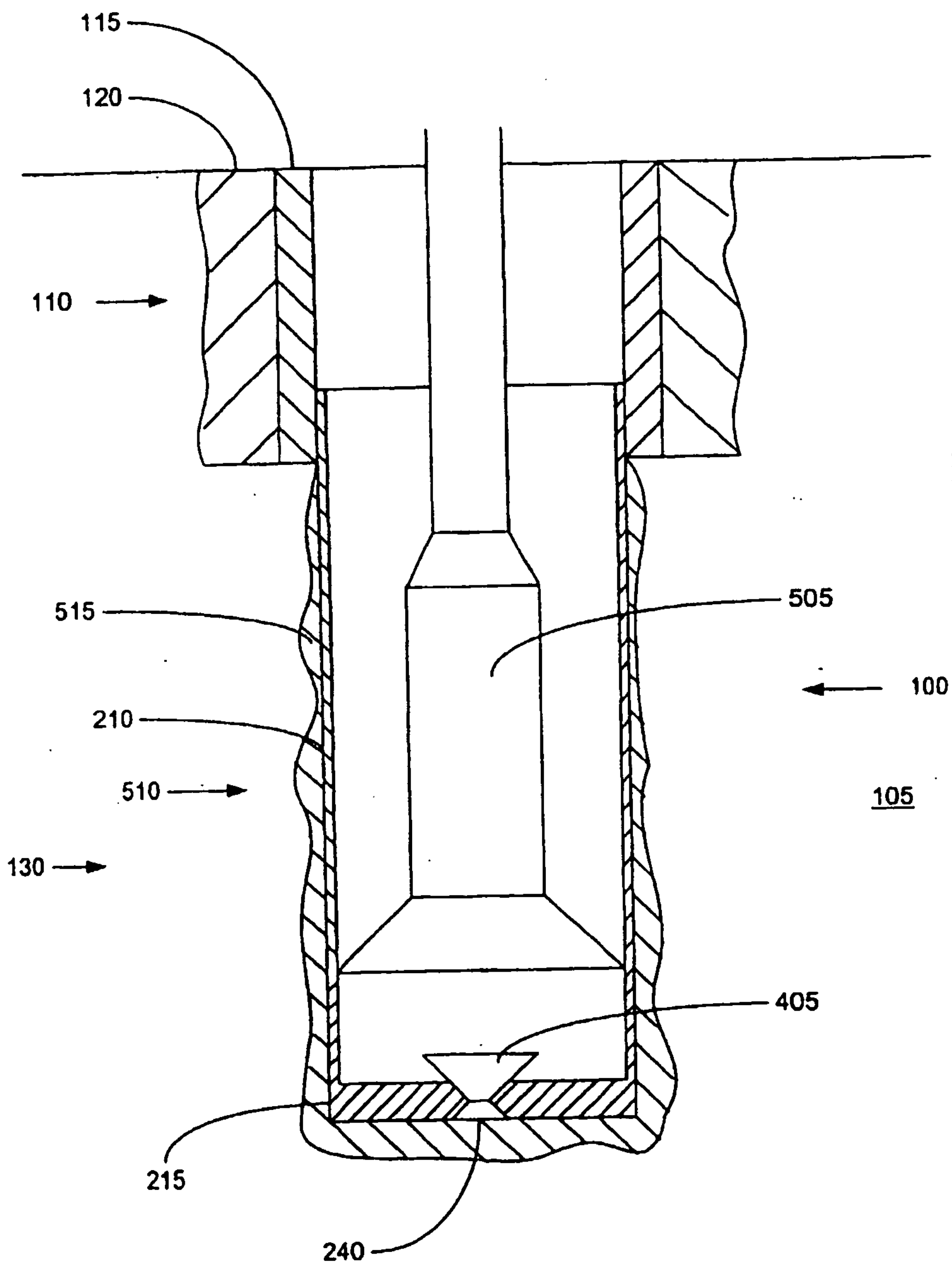


FIGURE 5

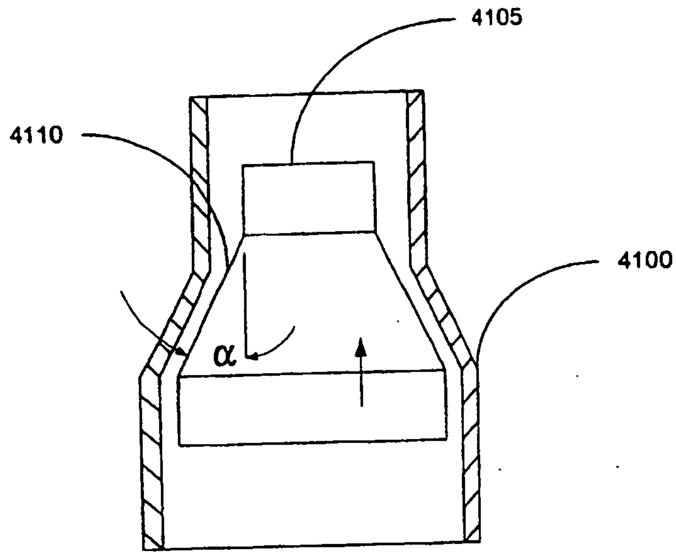
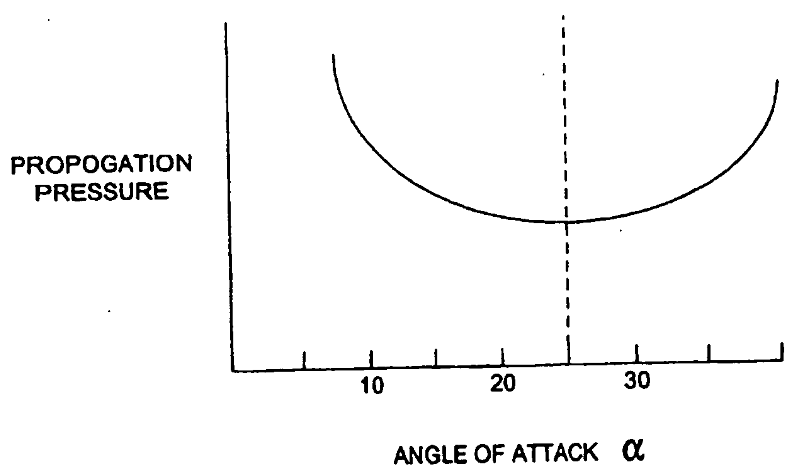


FIGURE 6



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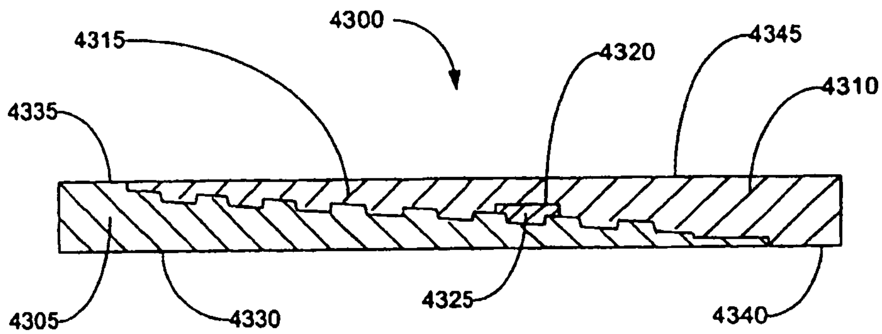

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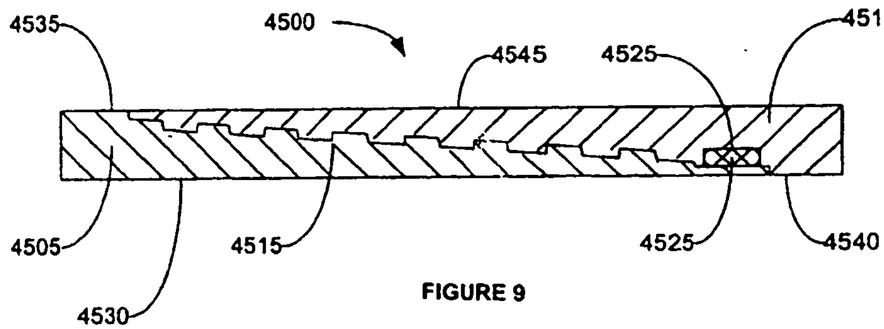

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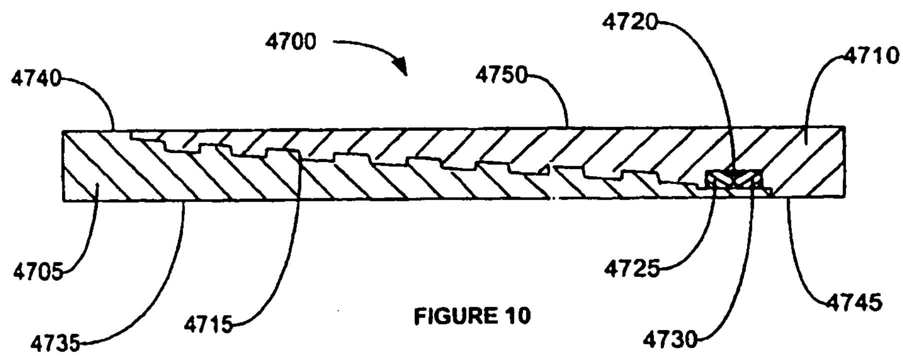

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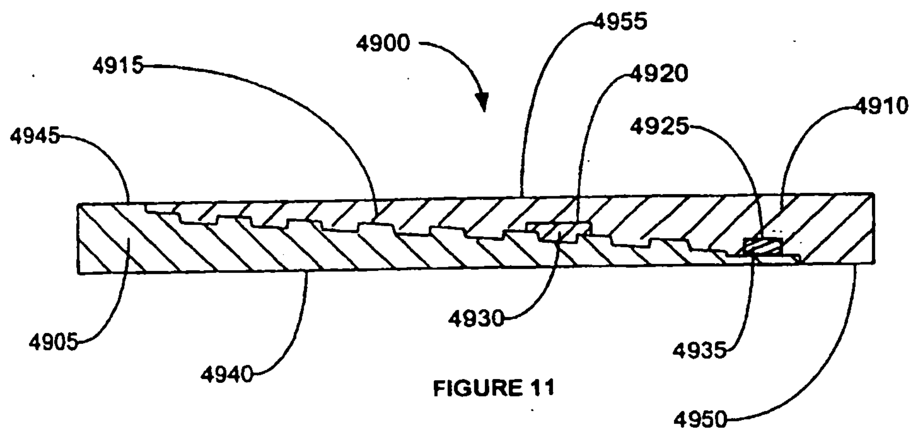

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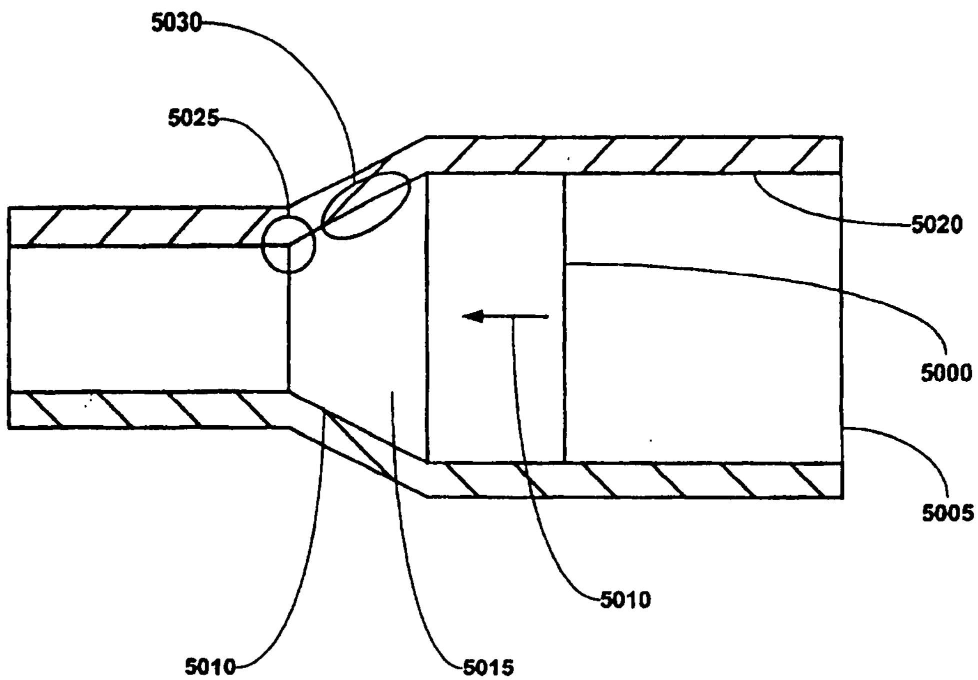

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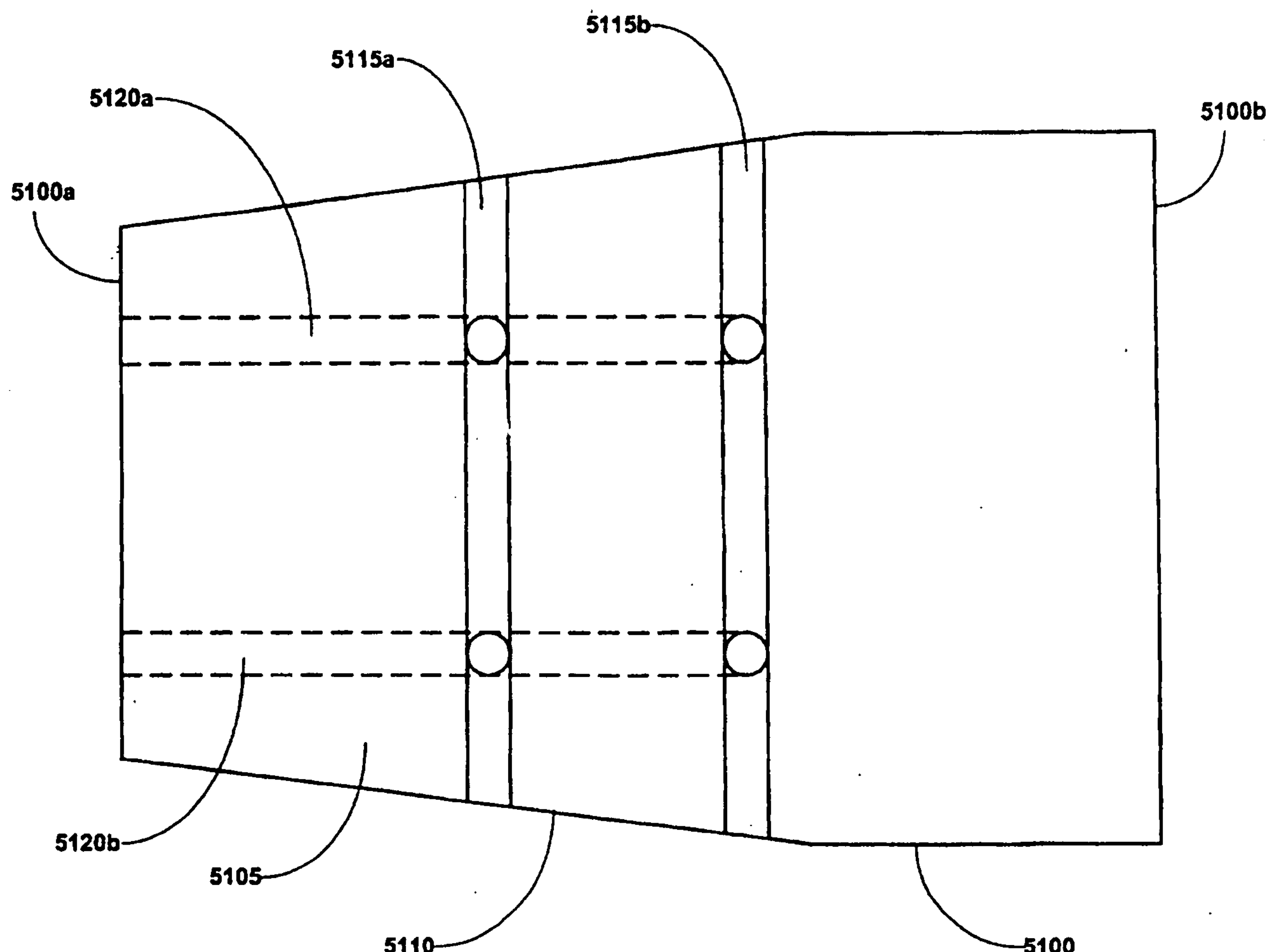

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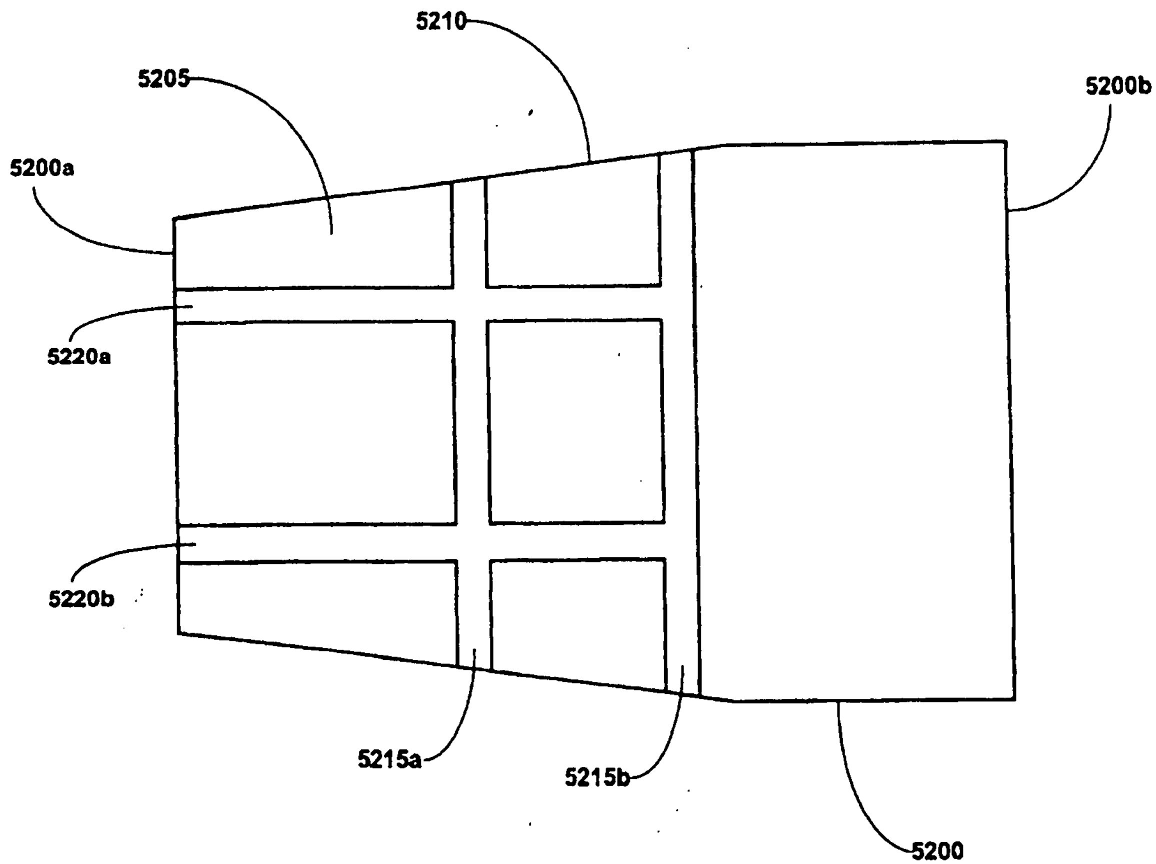

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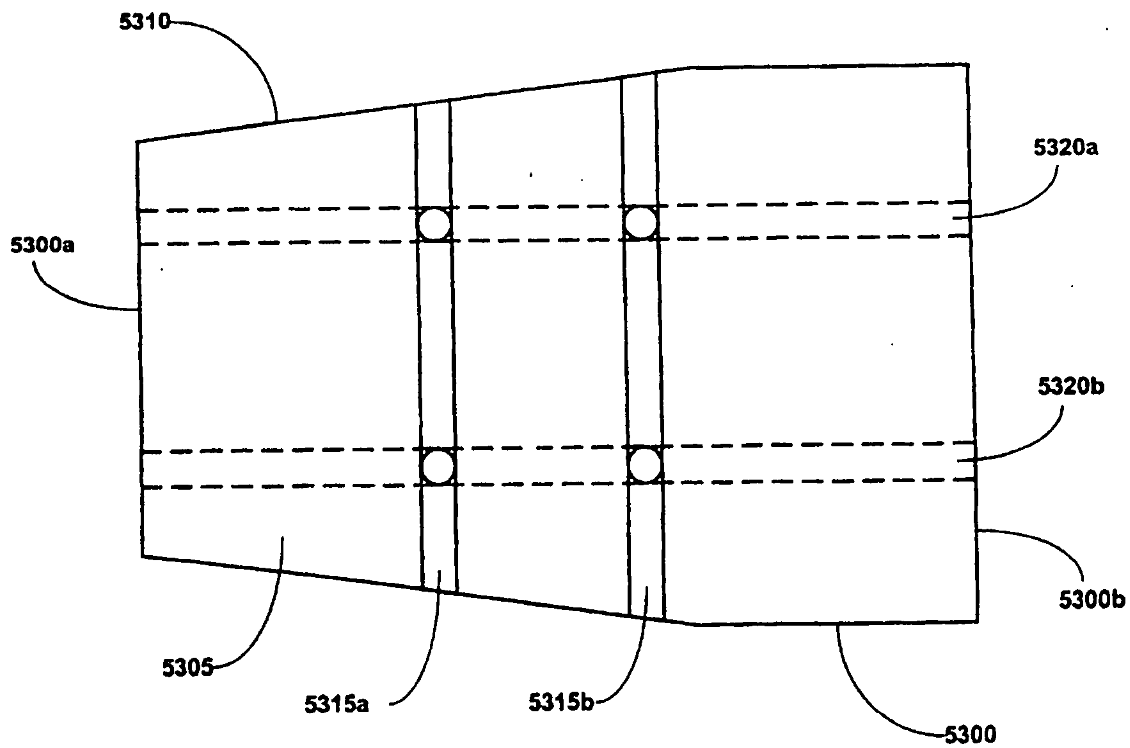

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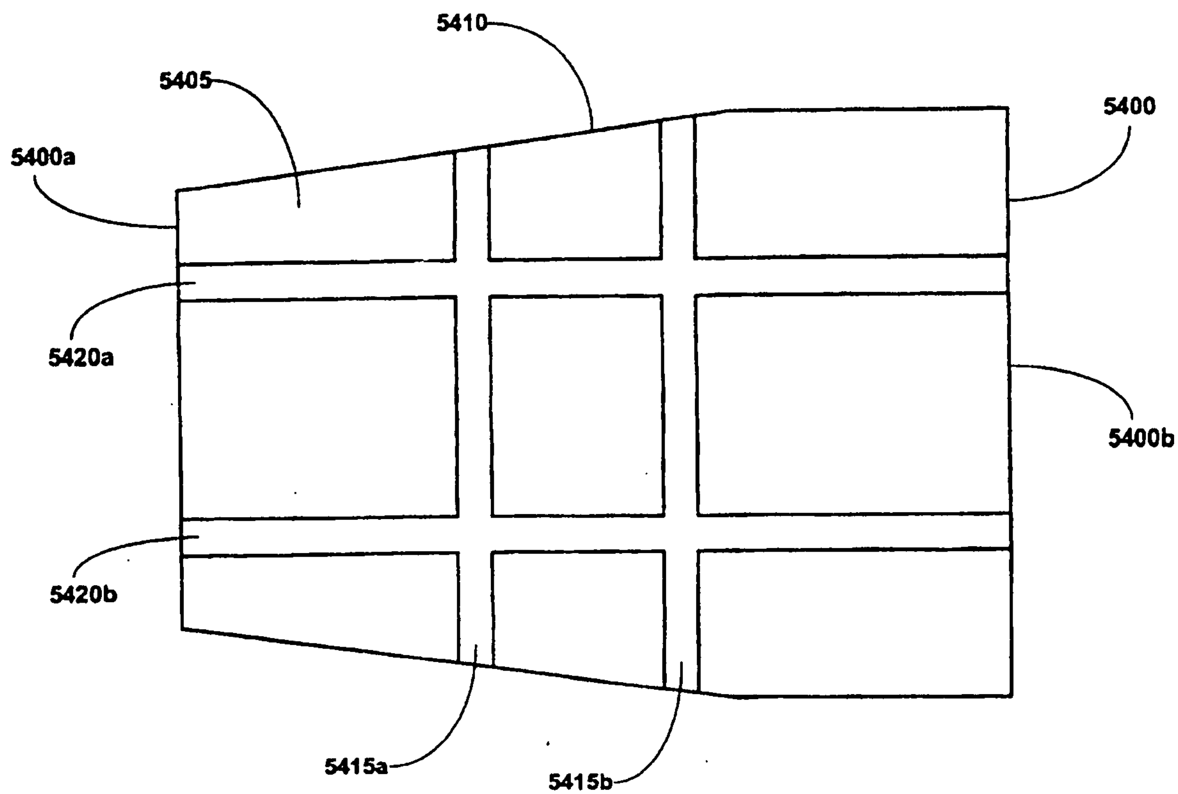


FIGURE 16

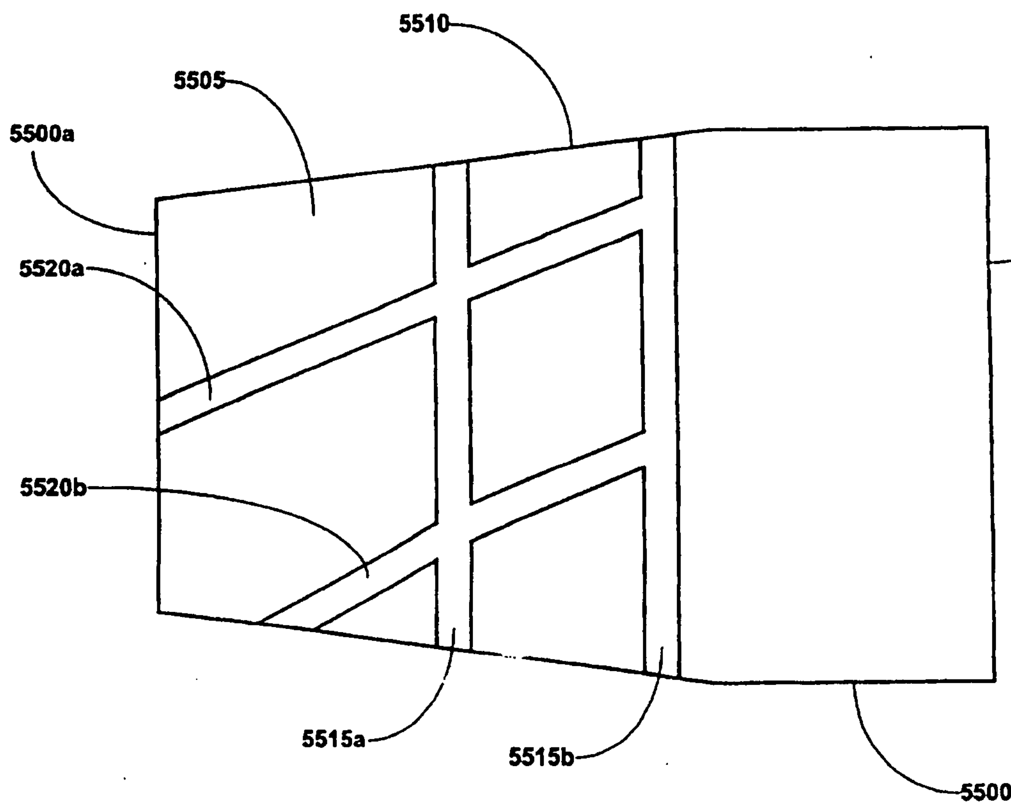
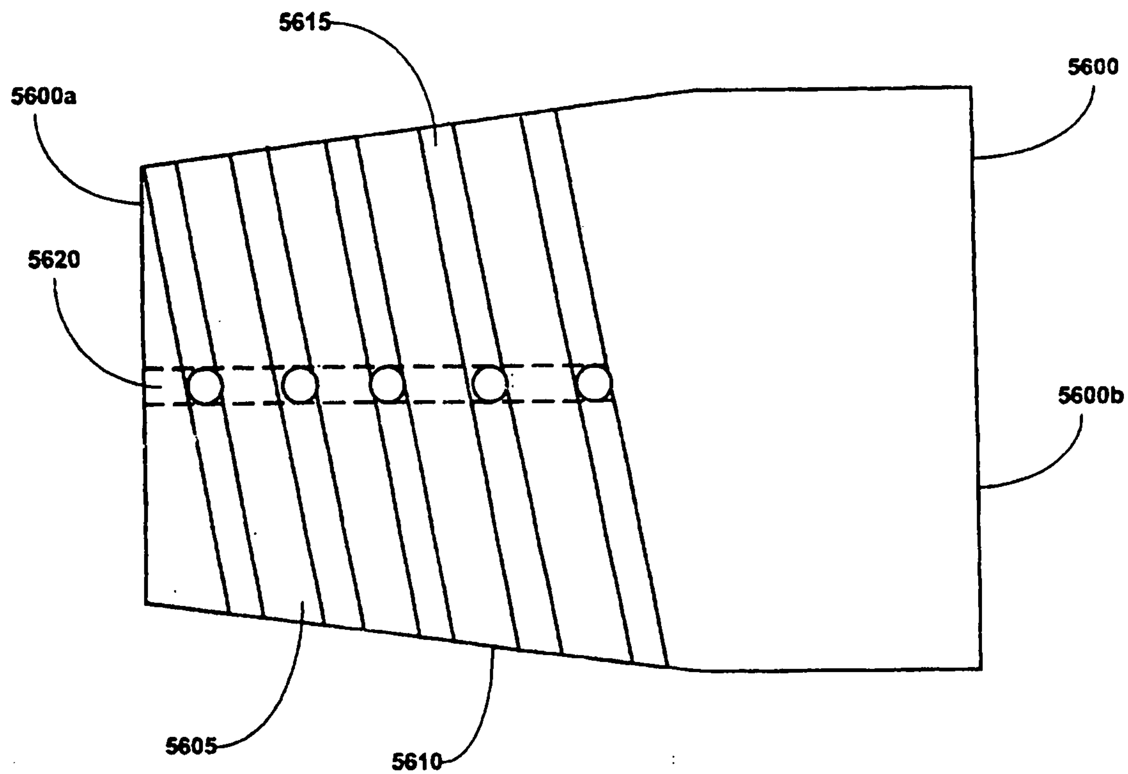


FIGURE 17



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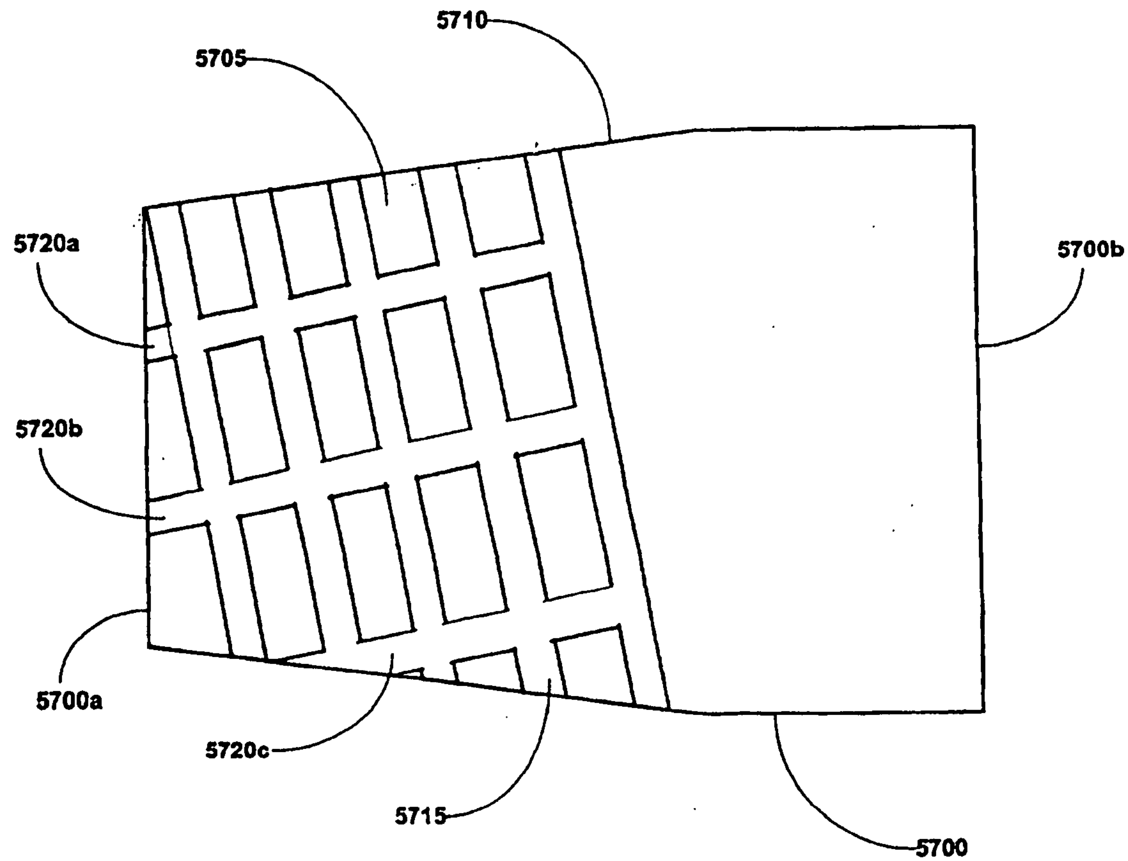
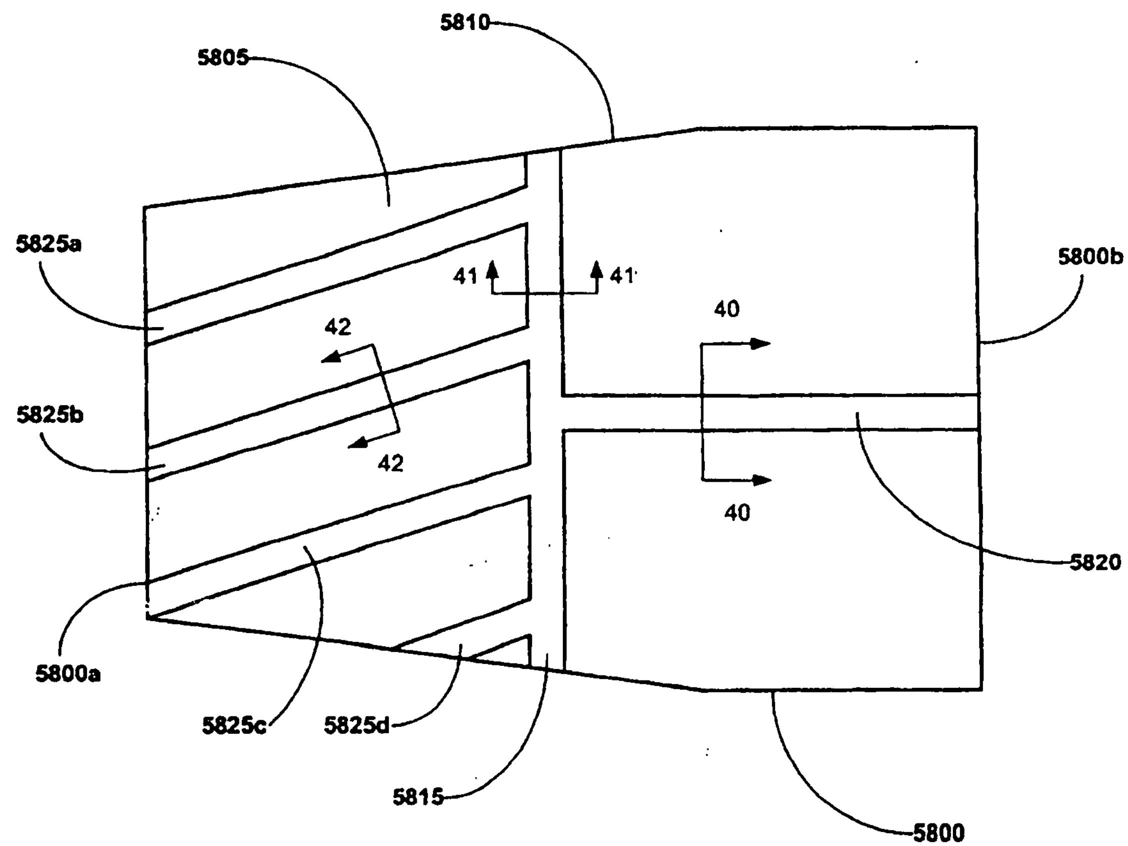


FIGURE 19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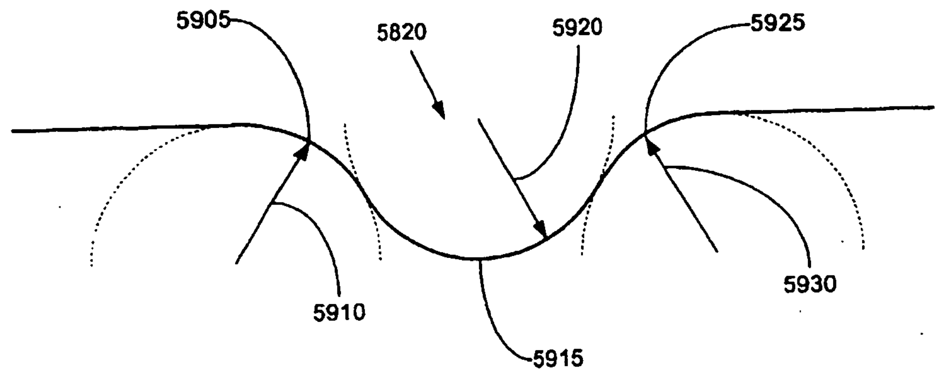
5800

FIGURE 20



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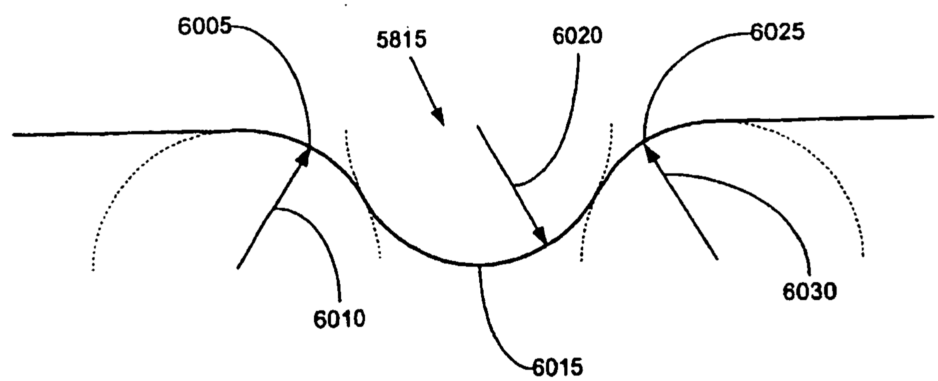

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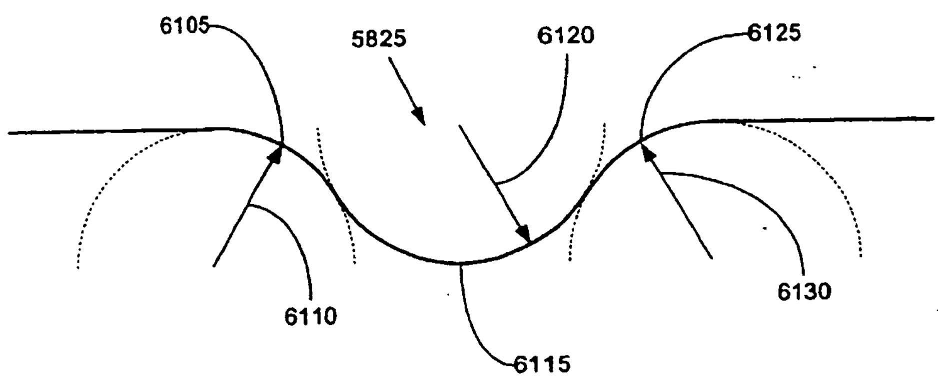

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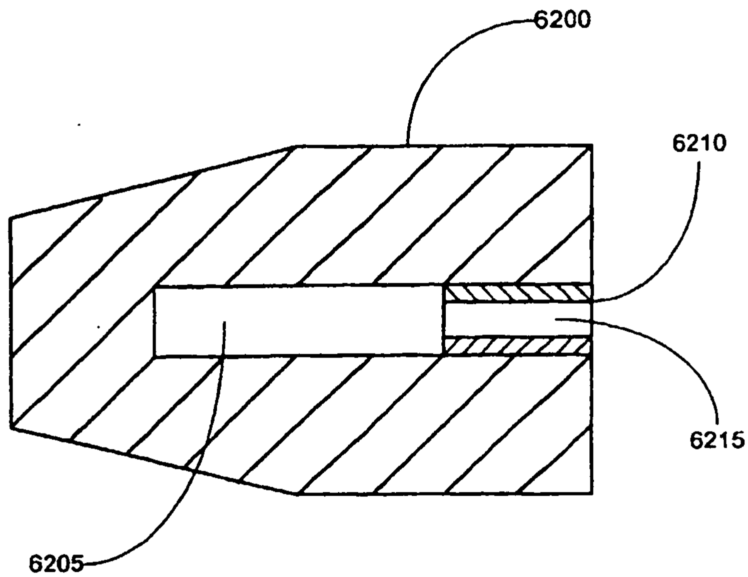

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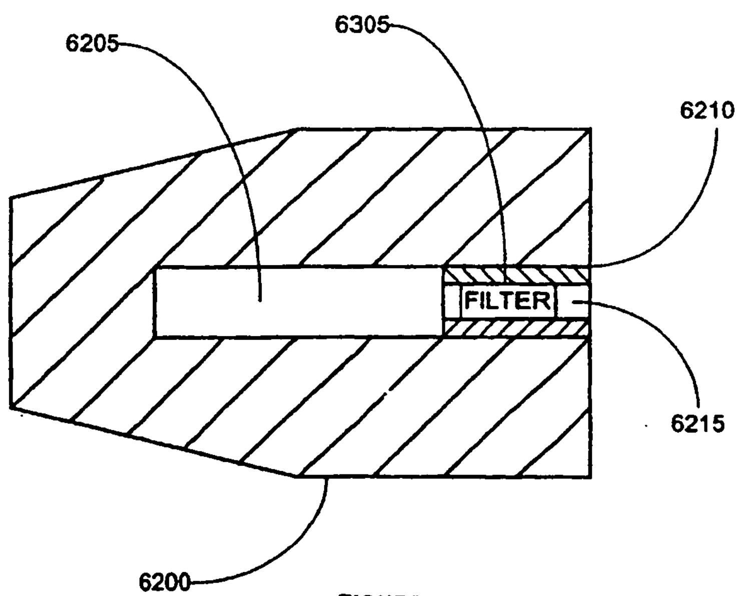

FIGURE 25

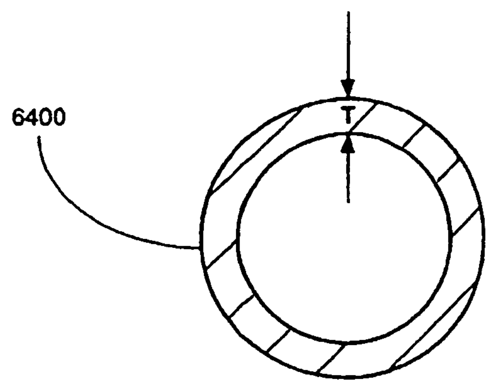

FIGURE 26

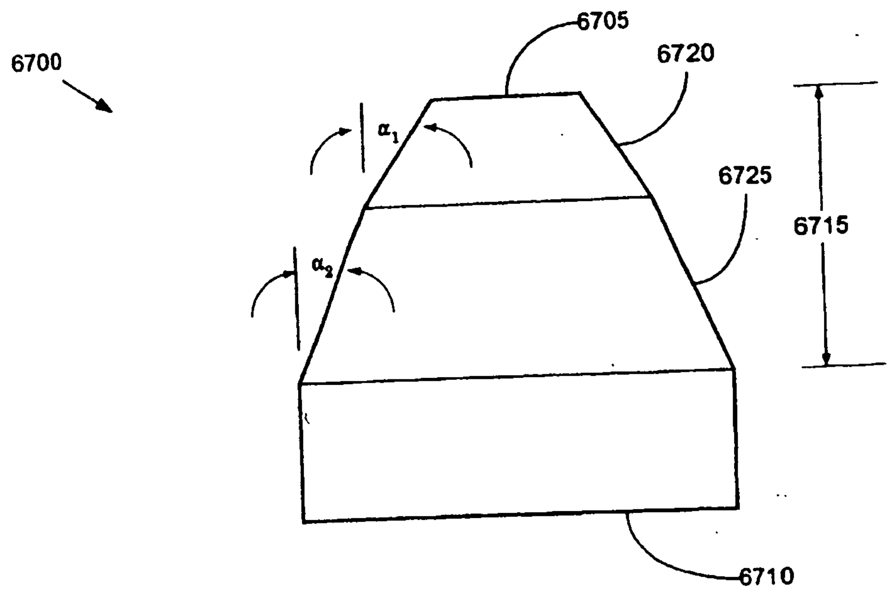

FIGURE 27

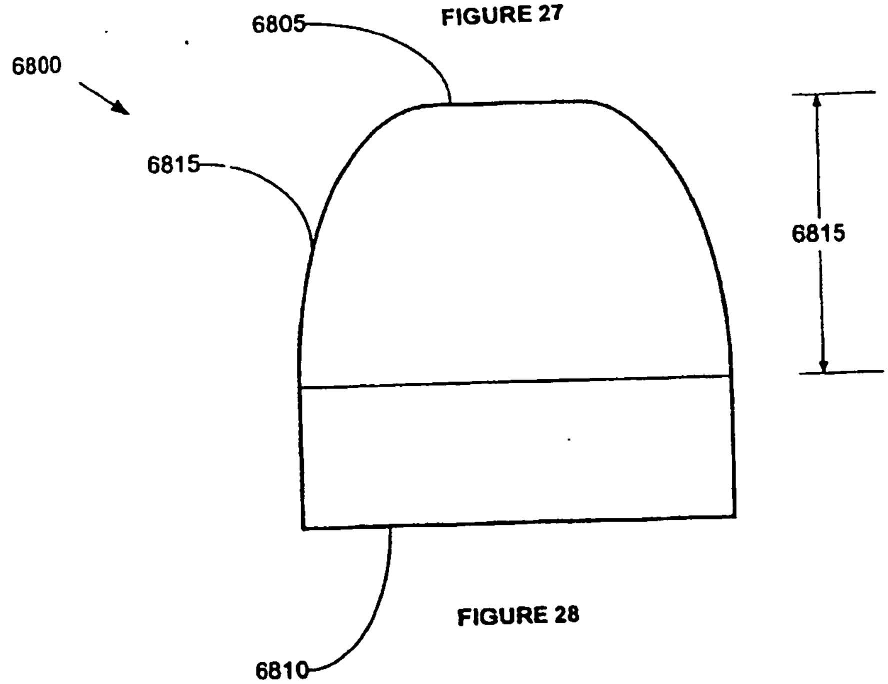

FIGURE 28

EXPANSION CONE 2392691

Cross Reference To Related Applications

This application claims the benefit of the filing date of U.S. provisional patent application serial no. 60/143,039, attorney docket no. 25791.26, filed on July 9, 1999, and U.S. provisional patent application serial no. 60/146,203, attorney docket no. 25791.25, filed on July 29,1999.

This application is related to the following co-pending applications: provisional patent application number 60/108,558, filed 11/16/1998, provisional patent application number 60/111,293, filed 12/7/1998, provisional patent application number 60/119,611, filed 2/11/1999, provisional patent application number 60/121,702, filed 2/25/1999, provisional patent application number 60/121,907, filed 2/26/1999, provisional patent application number 60/124,042, filed 3/11/1999, provisional patent application number 60/131,106, filed 4/26/1999, provisional patent application number 60/137,998, filed 6/7/1999, and provisional patent application number 60/143,039, attorney docket number 25791.26, filed on 7/9/1999.

Background of the Invention

This invention relates generally to an expansion cone.

Conventionally, when a wellbore is created, a number of casings are installed in the borehole to prevent collapse of the borehole wall and to prevent undesired outflow of drilling fluid into the formation or inflow of fluid from the formation into the borehole. The borehole is drilled in intervals whereby a casing which is to be installed in a lower borehole interval is lowered through a previously installed casing of an upper borehole interval. As a consequence of this procedure the casing of the lower interval is of smaller diameter than the casing of the upper interval. Thus, the casings are in a nested arrangement with casing diameters decreasing in downward direction. Cement annuli are provided between the outer surfaces of the casings and the borehole wall to seal the casings from the borehole wall. As a consequence of this nested arrangement a relatively large borehole diameter is required at the upper part of the wellbore. Such a large borehole diameter involves increased costs due to heavy casing handling equipment, large drill bits and increased volumes of drilling fluid and drill cuttings. Moreover, increased drilling rig time is involved due to required cement pumping, cement hardening, required equipment changes due to large variations in hole diameters drilled in the course of the well, and the large volume of cuttings drilled and removed.

Conventionally, at the surface end of the wellbore, a wellhead is formed that typically includes a surface casing, a number of production and/or drilling spools, valving, and a Christmas tree. Typically the wellhead further includes a concentric arrangement of casings including a production casing and one or more intermediate casings. The casings are typically supported using load bearing slips positioned above the ground. The conventional design and construction of wellheads is expensive and complex.

Conventionally, a wellbore casing cannot be formed during the drilling of a wellbore. Typically, the wellbore is drilled and then a wellbore casing is formed in the newly drilled section of the wellbore. This delays the completion of a well.

The present invention is directed to overcoming one or more of the limitations of the existing procedures for forming wellbores and wellheads.

Summary of the Invention

According to the present invention, there is provided an expansion cone for radially expanding a round tubular member in a wellbore from a first radial size to a second larger radial size, comprising:

an expansion cone body comprising a plurality of adjacent discrete tapered sections.

Preferably, the angle of attack of the adjacent discrete tapered sections increases in a continuous manner from one end of the expansion cone body to the opposite end of the expansion cone body.

Preferably, the plurality of adjacent discrete tapered sections comprises three or more adjacent discrete tapered sections.

Preferably, the expansion cone comprises a front end and a back end.

Preferably, a tapered section adjacent the front end comprises an angle of attack of about 8 to 20 degrees

Preferably, a tapered section adjacent the back end comprises an angle of attack of about 4 to 15 degrees.

Preferably, angles of attack of the adjacent discrete tapered sections decrease from the front end to the back end.

Preferably, the plurality of adjacent discrete tapered sections comprises a first tapered section adjacent the front end and a second tapered section adjacent the back end, the first tapered section comprising an angle of attack of about 8 to 20 degrees, and the second tapered section comprising an angle of attack of about 4 to 15 degrees.

Preferably, at least a portion of the expansion cone body has an angle of attack

of 25°.

Preferably, the expansion cone further comprises a lubricant on an outer surface of the expansion cone body.

Preferably, the expansion cone further comprises one or more grooves formed in an outer surface of the expansion cone body.

Preferably, the expansion cone further comprises one or more axial flow passages defined within the paraboloid expansion cone body.

Preferably, the grooves comprise circumferential grooves.

Preferably, the grooves comprise spiral grooves.

Preferably, the grooves are concentrated around an axial midpoint of the expansion cone body.

Preferably, the axial flow passages comprise axial grooves.

Preferably, the axial grooves are spaced apart by at least about 3 inches in the circumferential direction.

Preferably, the expansion cone further comprises one or more flow passages, wherein the flow passages are positioned within the expansion cone body.

Preferably, the flow passages are coupled to one or more grooves.

Preferably, one or more of the flow passages include inserts having restricted flow passages.

Preferably, one or more of the flow passages include filters.

Preferably, the cross-sectional area of the grooves ranges from 1.29×10^{-7} m^2 to 3.226×10^{-5} m^2 (2×10^{-4} in^2 to 5×10^{-2} in^2).

Preferably, the cross-sectional area of the axial flow passages ranges from about 1.29×10^{-7} m^2 to 3.226×10^{-5} m^2 (2×10^{-4} in^2 to 5×10^{-2} in^2).

Preferably, the grooves include:

a flow channel having a first radius of curvature;

a first shoulder positioned on one side of the flow channel having a second radius of curvature; and

a second shoulder positioned on the other side of the flow channel having a third radius of curvature.

Preferably, the first, second and third radii of curvature are substantially equal.

Preferably, the axial flow passages include:

a flow channel having a first radius of curvature;

a first shoulder positioned on one side of the flow channel having a second radius of curvature; and

a second shoulder positioned on the other side of the flow channel having a

third radius of curvature.

Preferably, the first, second and third radii of curvature are substantially equal.

Preferably, the second radius of curvature is greater than the third radius of curvature.

Brief Description of the Drawings

FIG. 1 is a fragmentary cross-sectional view illustrating the drilling of a new section of a well borehole.

FIG. 2 is a fragmentary cross-sectional view illustrating the placement of an embodiment of an apparatus for creating a casing within the new section of the well borehole.

FIG. 3 is a fragmentary cross-sectional view illustrating the injection of a first quantity of a fluidic material into the new section of the well borehole.

FIG. 3a is another fragmentary cross-sectional view illustrating the injection of a first quantity of a hardenable fluidic sealing material into the new section of the well borehole.

FIG. 4 is a fragmentary cross-sectional view illustrating the injection of a second quantity of a fluidic material into the new section of the well borehole.

FIG. 5 is a fragmentary cross-sectional view illustrating the drilling out of a portion of the cured hardenable fluidic sealing material from the new section of the well borehole.

FIG. 6 is a partial cross-sectional illustration of an expansion mandrel expanding a tubular member.

FIG. 7 is a graphical illustration of the relationship between propagation pressure and the angle of attack of the expansion mandrel.

FIG. 8 is a fragmentary cross-sectional illustration of the lubrication of the interface between an expansion mandrel and a tubular member during the radial expansion process.

FIG. 9 is an illustration of an embodiment of an expansion mandrel including a system for lubricating the interface between the expansion mandrel and a tubular member during the radial expansion of the tubular member.

FIG. 10 is an illustration of an embodiment of an expansion mandrel including a system for lubricating the interface between the expansion mandrel and a tubular member during the radial expansion of the tubular member.

FIG. 11 is an illustration of an embodiment of an expansion mandrel including a system for lubricating the interface between the expansion mandrel and a tubular member during the radial expansion of the tubular member.

FIG. 12 is an illustration of an embodiment of an expansion mandrel including a system for lubricating the interface between the expansion mandrel and a tubular member during the radial expansion of the tubular member.

FIG. 13 is an illustration of an embodiment of an expansion mandrel including a system for lubricating the interface between the expansion mandrel and a tubular member during the radial expansion of the tubular member.

FIG. 14 is an illustration of an embodiment of an expansion mandrel including a system for lubricating the interface between the expansion mandrel and a tubular member during the radial expansion of the tubular member.

FIG. 15 is an illustration of an embodiment of an expansion mandrel including a system for lubricating the interface between the expansion mandrel and a tubular member during the radial expansion of the tubular member.

FIG. 16 is an illustration of a preferred embodiment of an expansion mandrel including a system for lubricating the interface between the expansion mandrel and a tubular member during the radial expansion of the tubular member.

FIG. 17 is a cross-sectional illustration of the first axial groove of the expansion mandrel of FIG. 16.

FIG. 18 is a cross-sectional illustration of the circumferential groove of the expansion mandrel of FIG. 16.

FIG. 19 is a cross-sectional illustration of one of the second axial grooves of the expansion mandrel of FIG. 16.

FIG. 20 is a cross sectional illustration of an embodiment of an expansion mandrel including internal flow passages having inserts for adjusting the flow of lubricant fluids.

FIG. 21 is a cross sectional illustration of the expansion mandrel of FIG. 20 further including an insert having a filter for filtering out foreign materials from the lubricant fluids.

FIG. 22 is a cross sectional illustration of a preferred embodiment of an expandable tubular for use in forming and/or repairing a wellbore casing, pipeline, or foundation support.

FIG. 23 is an illustration of an embodiment of an expansion cone optimally adapted to radially expand a tubular member.

FIG. 24 is an illustration of another embodiment of an expansion cone optimally adapted to radially expand a tubular member.

Detailed Description of the Illustrative Embodiments

Referring initially to Figs. 1-5, an embodiment of an apparatus and method for forming a wellbore casing within a subterranean formation will now be described. As illustrated in Fig. 1, a wellbore 100 is positioned in a subterranean formation 105. The wellbore 100 includes an existing cased section 110 having a tubular casing 115 and an annular outer layer of cement 120.

In order to extend the wellbore 100 into the subterranean formation 105, a drill string 125 is used in a well known manner to drill out material from the subterranean formation 105 to form a new section 130.

As illustrated in Fig. 2, an apparatus 200 for forming a wellbore casing in a subterranean formation is then positioned in the new section 130 of the wellbore 100. The apparatus 200 preferably includes an expandable mandrel or pig 205, a tubular member 210, a shoe 215, a lower cup seal 220, an upper cup seal 225, a fluid passage 230, a fluid passage 235, a fluid passage 240, seals 245, and a support member 250.

The expandable mandrel 205 is coupled to and supported by the support member 250. The expandable mandrel 205 is preferably adapted to controllably expand in a radial direction. The expandable mandrel 205 may comprise any number of conventional commercially available expandable mandrels modified in accordance with the teachings of the present disclosure. In a preferred embodiment, the expandable mandrel 205 comprises a hydraulic expansion tool as disclosed in U.S. Patent No. 5,348,095, the contents of which are incorporated herein by reference, modified in accordance with the teachings of the present disclosure.

The tubular member 210 is supported by the expandable mandrel 205. The tubular member 210 is expanded in the radial direction and extruded off of the expandable mandrel 205. The tubular member 210 may be fabricated from any number of conventional commercially available materials such as, for example, Oilfield Country Tubular Goods (OCTG), 13 chromium steel tubing/casing, or plastic tubing/casing. In a preferred embodiment, the tubular member 210 is fabricated from OCTG in order to maximize strength after expansion. The inner and outer diameters of the tubular member 210 may range, for example, from approximately 0.75 to 47 inches and 1.05 to 48 inches, respectively. In a preferred embodiment, the inner and outer diameters of the tubular member 210 range from about 3 to 15.5 inches and 3.5 to 16 inches, respectively in order to optimally provide minimal telescoping effect in the most

commonly drilled wellbore sizes. The tubular member 210 preferably comprises a solid member.

In a preferred embodiment, the end portion 260 of the tubular member 210 is slotted, perforated, or otherwise modified to catch or slow down the mandrel 205 when it completes the extrusion of tubular member 210. In a preferred embodiment, the length of the tubular member 210 is limited to minimize the possibility of buckling. For typical tubular member 210 materials, the length of the tubular member 210 is preferably limited to between about 40 to 20,000 feet in length.

The shoe 215 is coupled to the expandable mandrel 205 and the tubular member 210. The shoe 215 includes fluid passage 240. The shoe 215 may comprise any number of conventional commercially available shoes such as, for example, Super Seal II float shoe, Super Seal II Down-Jet float shoe or a guide shoe with a sealing sleeve for a latch down plug modified in accordance with the teachings of the present disclosure. In a preferred embodiment, the shoe 215 comprises an aluminum down-jet guide shoe with a sealing sleeve for a latch-down plug available from Halliburton Energy Services in Dallas, TX, modified in accordance with the teachings of the present disclosure, in order to optimally guide the tubular member 210 in the wellbore, optimally provide an adequate seal between the interior and exterior diameters of the overlapping joint between the tubular members, and to optimally allow the complete drill out of the shoe and plug after the completion of the cementing and expansion operations.

In a preferred embodiment, the shoe 215 includes one or more through and side outlet ports in fluidic communication with the fluid passage 240. In this manner, the shoe 215 optimally injects hardenable fluidic sealing material into the region outside the shoe 215 and tubular member 210. In a preferred embodiment, the shoe 215 includes the fluid passage 240 having an inlet geometry that can receive a dart and/or a ball sealing member. In this manner, the fluid passage 240 can be optimally sealed off by introducing a plug, dart and/or ball sealing elements into the fluid passage 230.

The lower cup seal 220 is coupled to and supported by the support member 250. The lower cup seal 220 prevents foreign materials from entering the interior region of the tubular member 210 adjacent to the expandable mandrel 205. The lower cup seal 220 may comprise any number of conventional commercially available cup seals such as, for example, TP cups, or Selective Injection Packer (SIP) cups modified in accordance with the teachings of the present disclosure. In a preferred embodiment, the lower cup seal 220 comprises a SIP cup seal, available from Halliburton Energy

Services in Dallas, TX in order to optimally block foreign material and contain a body of lubricant.

The upper cup seal 225 is coupled to and supported by the support member 250. The upper cup seal 225 prevents foreign materials from entering the interior region of the tubular member 210. The upper cup seal 225 may comprise any number of conventional commercially available cup seals such as, for example, TP cups or SIP cups modified in accordance with the teachings of the present disclosure. In a preferred embodiment, the upper cup seal 225 comprises a SIP cup, available from Halliburton Energy Services in Dallas, TX in order to optimally block the entry of foreign materials and contain a body of lubricant.

The fluid passage 230 permits fluidic materials to be transported to and from the interior region of the tubular member 210 below the expandable mandrel 205. The fluid passage 230 is coupled to and positioned within the support member 250 and the expandable mandrel 205. The fluid passage 230 preferably extends from a position adjacent to the surface to the bottom of the expandable mandrel 205. The fluid passage 230 is preferably positioned along a centerline of the apparatus 200.

The fluid passage 230 is preferably selected, in the casing running mode of operation, to transport materials such as drilling mud or formation fluids at flow rates and pressures ranging from about 0 to 3,000 gallons/minute and 0 to 9,000 psi in order to minimize drag on the tubular member being run and to minimize surge pressures exerted on the wellbore which could cause a loss of wellbore fluids and lead to hole collapse.

The fluid passage 235 permits fluidic materials to be released from the fluid passage 230. In this manner, during placement of the apparatus 200 within the new section 130 of the wellbore 100, fluidic materials 255 forced up the fluid passage 230 can be released into the wellbore 100 above the tubular member 210 thereby minimizing surge pressures on the wellbore section 130. The fluid passage 235 is coupled to and positioned within the support member 250. The fluid passage is further fluidicly coupled to the fluid passage 230.

The fluid passage 235 preferably includes a control valve for controllably opening and closing the fluid passage 235. In a preferred embodiment, the control valve is pressure activated in order to controllably minimize surge pressures. The fluid passage 235 is preferably positioned substantially orthogonal to the centerline of the apparatus 200.

The fluid passage 235 is preferably selected to convey fluidic materials at flow rates and pressures ranging from about 0 to 3,000 gallons/minute and 0 to 9,000 psi in

order to reduce the drag on the apparatus 200 during insertion into the new section 130 of the wellbore 100 and to minimize surge pressures on the new wellbore section 130.

The fluid passage 240 permits fluidic materials to be transported to and from the region exterior to the tubular member 210 and shoe 215. The fluid passage 240 is coupled to and positioned within the shoe 215 in fluidic communication with the interior region of the tubular member 210 below the expandable mandrel 205. The fluid passage 240 preferably has a cross-sectional shape that permits a plug, or other similar device, to be placed in fluid passage 240 to thereby block further passage of fluidic materials. In this manner, the interior region of the tubular member 210 below the expandable mandrel 205 can be fluidicly isolated from the region exterior to the tubular member 210. This permits the interior region of the tubular member 210 below the expandable mandrel 205 to be pressurized. The fluid passage 240 is preferably positioned substantially along the centerline of the apparatus 200.

The fluid passage 240 is preferably selected to convey materials such as cement, drilling mud or epoxies at flow rates and pressures ranging from about 0 to 3,000 gallons/minute and 0 to 9,000 psi in order to optimally fill the annular region between the tubular member 210 and the new section 130 of the wellbore 100 with fluidic materials. In a preferred embodiment, the fluid passage 240 includes an inlet geometry that can receive a dart and/or a ball sealing member. In this manner, the fluid passage 240 can be sealed off by introducing a plug, dart and/or ball sealing elements into the fluid passage 230.

The seals 245 are coupled to and supported by an end portion 260 of the tubular member 210. The seals 245 are further positioned on an outer surface 265 of the end portion 260 of the tubular member 210. The seals 245 permit the overlapping joint between the end portion 270 of the casing 115 and the portion 260 of the tubular member 210 to be fluidicly sealed. The seals 245 may comprise any number of conventional commercially available seals such as, for example, lead, rubber, Teflon, or epoxy seals modified in accordance with the teachings of the present disclosure. In a preferred embodiment, the seals 245 are molded from Stratalock epoxy available from Halliburton Energy Services in Dallas, TX in order to optimally provide a load bearing interference fit between the end 260 of the tubular member 210 and the end 270 of the existing casing 115.

In a preferred embodiment, the seals 245 are selected to optimally provide a sufficient frictional force to support the expanded tubular member 210 from the existing casing 115. In a preferred embodiment, the frictional force optimally provided by the

seals 245 ranges from about 1,000 to 1,000,000 lbf in order to optimally support the expanded tubular member 210.

The support member 250 is coupled to the expandable mandrel 205, tubular member 210, shoe 215, and seals 220 and 225. The support member 250 preferably comprises an annular member having sufficient strength to carry the apparatus 200 into the new section 130 of the wellbore 100. In a preferred embodiment, the support member 250 further includes one or more conventional centralizers (not illustrated) to help stabilize the apparatus 200. In a preferred embodiment, the support member 250 comprises coiled tubing.

In a preferred embodiment, a quantity of lubricant 275 is provided in the annular region above the expandable mandrel 205 within the interior of the tubular member 210. In this manner, the extrusion of the tubular member 210 off of the expandable mandrel 205 is facilitated. The lubricant 275 may comprise any number of conventional commercially available lubricants such as, for example, Lubriplate, chlorine based lubricants, oil based lubricants or Climax 1500 Antisieze (3100). In a preferred embodiment, the lubricant 275 comprises Climax 1500 Antisieze (3100) available from Climax Lubricants and Equipment Co. in Houston, TX in order to optimally provide optimum lubrication to facilitate the expansion process.

In a preferred embodiment, the support member 250 is thoroughly cleaned prior to assembly to the remaining portions of the apparatus 200. In this manner, the introduction of foreign material into the apparatus 200 is minimized. This minimizes the possibility of foreign material clogging the various flow passages and valves of the apparatus 200.

In a preferred embodiment, before or after positioning the apparatus 200 within the new section 130 of the wellbore 100, a couple of wellbore volumes are circulated in order to ensure that no foreign materials are located within the wellbore 100 that might clog up the various flow passages and valves of the apparatus 200 and to ensure that no foreign material interferes with the expansion process.

As illustrated in Fig. 3, the fluid passage 235 is then closed and a hardenable fluidic sealing material 305 is then pumped from a surface location into the fluid passage 230. The material 305 then passes from the fluid passage 230 into the interior region 310 of the tubular member 210 below the expandable mandrel 205. The material 305 then passes from the interior region 310 into the fluid passage 240. The material 305 then exits the apparatus 200 and fills the annular region 315 between the exterior of the tubular member 210 and the interior wall of the new section 130 of the

wellbore 100. Continued pumping of the material 305 causes the material 305 to fill up at least a portion of the annular region 315.

The material 305 is preferably pumped into the annular region 315 at pressures and flow rates ranging, for example, from about 0 to 5000 psi and 0 to 1,500 gallons/min, respectively. The optimum flow rate and operating pressures vary as a function of the casing and wellbore sizes, wellbore section length, available pumping equipment, and fluid properties of the fluidic material being pumped. The optimum flow rate and operating pressure are preferably determined using conventional empirical methods.

The hardenable fluidic sealing material 305 may comprise any number of conventional commercially available hardenable fluidic sealing materials such as, for example, slag mix, cement or epoxy. In a preferred embodiment, the hardenable fluidic sealing material 305 comprises a blended cement prepared specifically for the particular well section being drilled from Halliburton Energy Services in Dallas, TX in order to provide optimal support for tubular member 210 while also maintaining optimum flow characteristics so as to minimize difficulties during the displacement of cement in the annular region 315. The optimum blend of the blended cement is preferably determined using conventional empirical methods.

The annular region 315 preferably is filled with the material 305 in sufficient quantities to ensure that, upon radial expansion of the tubular member 210, the annular region 315 of the new section 130 of the wellbore 100 will be filled with material 305.

In a particularly preferred embodiment, as illustrated in Fig. 3a, the wall thickness and/or the outer diameter of the tubular member 210 is reduced in the region adjacent to the mandrel 205 in order optimally permit placement of the apparatus 200 in positions in the wellbore with tight clearances. Furthermore, in this manner, the initiation of the radial expansion of the tubular member 210 during the extrusion process is optimally facilitated.

As illustrated in Fig. 4, once the annular region 315 has been adequately filled with material 305, a plug 405, or other similar device, is introduced into the fluid passage 240 thereby fluidicly isolating the interior region 310 from the annular region 315. In a preferred embodiment, a non-hardenable fluidic material 306 is then pumped into the interior region 310 causing the interior region to pressurize. In this manner, the interior of the expanded tubular member 210 will not contain significant amounts of cured material 305. This reduces and simplifies the cost of the entire process. Alternatively, the material 305 may be used during this phase of the process. Once the interior region 310 becomes sufficiently pressurized, the tubular member 210 is

extruded off of the expandable mandrel 205. During the extrusion process, the expandable mandrel 205 may be raised out of the expanded portion of the tubular member 210. In a preferred embodiment, during the extrusion process, the mandrel 205 is raised at approximately the same rate as the tubular member 210 is expanded in order to keep the tubular member 210 stationary relative to the new wellbore section 130. In an alternative preferred embodiment, the extrusion process is commenced with the tubular member 210 positioned above the bottom of the new wellbore section 130, keeping the mandrel 205 stationary, and allowing the tubular member 210 to extrude off of the mandrel 205 and fall down the new wellbore section 130 under the force of gravity.

The plug 405 is preferably placed into the fluid passage 240 by introducing the plug 405 into the fluid passage 230 at a surface location in a conventional manner. The plug 405 preferably acts to fluidicly isolate the hardenable fluidic sealing material 305 from the non hardenable fluidic material 306.

The plug 405 may comprise any number of conventional commercially available devices from plugging a fluid passage such as, for example, Multiple Stage Cementer (MSC) latch-down plug, Omega latch-down plug or three-wiper latch-down plug modified in accordance with the teachings of the present disclosure. In a preferred embodiment, the plug 405 comprises a MSC latch-down plug available from Halliburton Energy Services in Dallas, TX.

After placement of the plug 405 in the fluid passage 240, a non hardenable fluidic material 306 is preferably pumped into the interior region 310 at pressures and flow rates ranging, for example, from approximately 400 to 10,000 psi and 30 to 4,000 gallons/min. In this manner, the amount of hardenable fluidic sealing material within the interior 310 of the tubular member 210 is minimized. In a preferred embodiment, after placement of the plug 405 in the fluid passage 240, the non hardenable material 306 is preferably pumped into the interior region 310 at pressures and flow rates ranging from approximately 500 to 9,000 psi and 40 to 3,000 gallons/min in order to maximize the extrusion speed.

In a preferred embodiment, the apparatus 200 is adapted to minimize tensile, burst, and friction effects upon the tubular member 210 during the expansion process. These effects will depend upon the geometry of the expansion mandrel 205, the material composition of the tubular member 210 and expansion mandrel 205, the inner diameter of the tubular member 210, the wall thickness of the tubular member 210, the type of lubricant, and the yield strength of the tubular member 210. In general, the thicker the wall thickness, the smaller the inner diameter, and the greater the yield

strength of the tubular member 210, then the greater the operating pressures required to extrude the tubular member 210 off of the mandrel 205.

For typical tubular members 210, the extrusion of the tubular member 210 off of the expandable mandrel will begin when the pressure of the interior region 310 reaches, for example, approximately 500 to 9,000 psi.

During the extrusion process, the expandable mandrel 205 may be raised out of the expanded portion of the tubular member 210 at rates ranging, for example, from about 0 to 5 ft/sec. In a preferred embodiment, during the extrusion process, the expandable mandrel 205 is raised out of the expanded portion of the tubular member 210 at rates ranging from about 0 to 2 ft/sec in order to minimize the time required for the expansion process while also permitting easy control of the expansion process.

When the end portion 260 of the tubular member 210 is extruded off of the expandable mandrel 205, the outer surface 265 of the end portion 260 of the tubular member 210 will preferably contact the interior surface 410 of the end portion 270 of the casing 115 to form an fluid tight overlapping joint. The contact pressure of the overlapping joint may range, for example, from approximately 50 to 20,000 psi. In a preferred embodiment, the contact pressure of the overlapping joint ranges from approximately 400 to 10,000 psi in order to provide optimum pressure to activate the annular sealing members 245 and optimally provide resistance to axial motion to accommodate typical tensile and compressive loads.

The overlapping joint between the section 410 of the existing casing 115 and the section 265 of the expanded tubular member 210 preferably provides a gaseous and fluidic seal. In a particularly preferred embodiment, the sealing members 245 optimally provide a fluidic and gaseous seal in the overlapping joint.

In a preferred embodiment, the operating pressure and flow rate of the non hardenable fluidic material 306 is controllably ramped down when the expandable mandrel 205 reaches the end portion 260 of the tubular member 210. In this manner, the sudden release of pressure caused by the complete extrusion of the tubular member 210 off of the expandable mandrel 205 can be minimized. In a preferred embodiment, the operating pressure is reduced in a substantially linear fashion from 100% to about 10% during the end of the extrusion process beginning when the mandrel 205 is within about 5 feet from completion of the extrusion process.

Alternatively, or in combination, a shock absorber is provided in the support member 250 in order to absorb the shock caused by the sudden release of pressure. The shock absorber may comprise, for example, any conventional commercially available shock absorber adapted for use in wellbore operations.

Alternatively, or in combination, a mandrel catching structure is provided in the end portion 260 of the tubular member 210 in order to catch or at least decelerate the mandrel 205.

Once the extrusion process is completed, the expandable mandrel 205 is removed from the wellbore 100. In a preferred embodiment, either before or after the removal of the expandable mandrel 205, the integrity of the fluidic seal of the overlapping joint between the upper portion 260 of the tubular member 210 and the lower portion 270 of the casing 115 is tested using conventional methods.

If the fluidic seal of the overlapping joint between the upper portion 260 of the tubular member 210 and the lower portion 270 of the casing 115 is satisfactory, then any uncured portion of the material 305 within the expanded tubular member 210 is then removed in a conventional manner such as, for example, circulating the uncured material out of the interior of the expanded tubular member 210. The mandrel 205 is then pulled out of the wellbore section 130 and a drill bit or mill is used in combination with a conventional drilling assembly 505 to drill out any hardened material 305 within the tubular member 210. The material 305 within the annular region 315 is then allowed to cure.

As illustrated in Fig. 5, preferably any remaining cured material 305 within the interior of the expanded tubular member 210 is then removed in a conventional manner using a conventional drill string 505. The resulting new section of casing 510 includes the expanded tubular member 210 and an outer annular layer 515 of cured material 305. The bottom portion of the apparatus 200 comprising the shoe 215 and dart 405 may then be removed by drilling out the shoe 215 and dart 405 using conventional drilling methods.

Referring to Figs. 6 and 7, the optimal relationship between the angle of attack of an expansion mandrel and the minimally required propagation pressure during the expansion of a tubular member will now be described. As illustrated in Fig. 6, during the radial expansion of a tubular member 4100 by an expansion mandrel 4105, the expansion mandrel 4105 is displaced in the axial direction. The angle of attack α of the conical surface 4110 of the expansion mandrel 4105 directly affects the required propagation pressure P_{PR} necessary to radially expand the tubular member 4100. Referring to Fig. 7, for typical grades of materials and typical geometries, the propagation pressure P_{PR} is minimized for an angle of attack of approximately 25 degrees. Furthermore, the optimal range of the angle of attack α ranges from about 10 to 30 degrees in order to minimize the range of required minimum propagation pressure P_{PR}.

Referring to Fig. 8, the lubrication of the interface between an expansion mandrel and a tubular member during the radial expansion process will now be described. As illustrated in Fig. 8, during the radial expansion process, an expansion cone 5000 radially expands a tubular member 5005 by moving in an axial direction 5010 relative to the tubular member 5005. The interface between the outer surface 5010 of the tapered portion 5015 of the expansion cone 5000 and the inner surface 5020 of the tubular member 5005 includes a leading edge portion 5025 and a trailing edge portion 5030.

During the radial expansion process, the leading edge portion 5025 is preferably lubricated by the presence of lubricating fluids provided ahead of the expansion cone 5000. However, because the radial clearance between the expansion cone 5000 and the tubular member 5005 in the trailing edge portion 5030 during the radial expansion process is typically extremely small, and the operating contact pressures between the tubular member 5005 and the expansion mandrel 5000 are extremely high, the quantity of lubricating fluid provided to the trailing edge portion 5030 is typically greatly reduced. In typical radial expansion operations, this reduction in lubrication in the trailing edge portion 5030 increases the forces required to radially expand the tubular member 5005.

Referring to Fig. 9, an embodiment of a system for lubricating the interface between an expansion cone and a tubular member during the expansion process will now be described. As illustrated in Fig. 9, an expansion cone 5100, having a front end 5100a and a rear end 5100b, includes a tapered portion 5105 having an outer surface 3110, one or more circumferential grooves 5115a and 5115b, and one more internal flow passages 5120a and 5120b.

In a preferred embodiment, the circumferential grooves 5115 are fluidicly coupled to the internal flow passages 5120. In this manner, during the radial expansion process, lubricating fluids are transmitted from the area ahead of the front 5100a of the expansion cone 5100 into the circumferential grooves 5115. Thus, the trailing edge portion of the interface between the expansion cone 5100 and a tubular member is provided with an increased supply of lubricant, thereby reducing the amount of force required to radially expand the tubular member. In a preferred embodiment, the lubricating fluids are injected into the internal flow passages 5120 using a fluid conduit that is coupled to the tapered end 5105 of the expansion cone 5100. Alternatively, lubricating fluids are provided for the internal flow passages 5120 using a supply of lubricating fluids provided adjacent to the front 5100a of the expansion cone 5100.

In a preferred embodiment, the expansion cone 5100 includes a plurality of circumferential grooves 5115. In a preferred embodiment, the cross sectional area of the circumferential grooves 5115 range from about $2X10^{-4}$ in^2 to $5X10^{-2}$ in^2 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5100 and a tubular member during the radial expansion process. In a preferred embodiment, the expansion cone 5100 includes circumferential grooves 5115 concentrated about the axial midpoint of the tapered portion 5105 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5100 and a tubular member during the radial expansion process. In a preferred embodiment, the circumferential grooves 5115 are equally spaced along the trailing edge portion of the expansion cone 5100 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5100 and a tubular member during the radial expansion process.

In a preferred embodiment, the expansion cone 5100 includes a plurality of flow passages 5120 coupled to each of the circumferential grooves 5115. In a preferred embodiment, the cross-sectional area of the flow passages 5120 ranges from about $2X10^{-4}$ in^2 to $5X10^{-2}$ in^2 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5100 and a tubular member during the radial expansion process. In a preferred embodiment, the cross sectional area of the circumferential grooves 5115 is greater than the cross sectional area of the flow passage 5120 in order to minimize resistance to fluid flow.

Referring to Fig. 10, another embodiment of a system for lubricating the interface between an expansion cone and a tubular member during the expansion process will now be described. As illustrated in Fig. 10, an expansion cone 5200, having a front end 5200a and a rear end 5200b, includes a tapered portion 5205 having an outer surface 5210, one or more circumferential grooves 5215a and 5215b, and one or more axial grooves 5220a and 5220b.

In a preferred embodiment, the circumferential grooves 5215 are fluidicly coupled to the axial groves 5220. In this manner, during the radial expansion process, lubricating fluids are transmitted from the area ahead of the front 5200a of the expansion cone 5200 into the circumferential grooves 5215. Thus, the trailing edge portion of the interface between the expansion cone 5200 and a tubular member is provided with an increased supply of lubricant, thereby reducing the amount of force required to radially expand the tubular member. In a preferred embodiment, the axial grooves 5220 are provided with lubricating fluid using a supply of lubricating fluid positioned proximate the front end 5200a of the expansion cone 5200. In a preferred

embodiment, the circumferential grooves 3215 are concentrated about the axial midpoint of the tapered portion 5205 of the expansion cone 5200 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5200 and a tubular member during the radial expansion process. In a preferred embodiment, the circumferential grooves 5215 are equally spaced along the trailing edge portion of the expansion cone 5200 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5200 and a tubular member during the radial expansion process.

In a preferred embodiment, the expansion cone 5200 includes a plurality of circumferential grooves 5215. In a preferred embodiment, the cross sectional area of the circumferential grooves 5215 range from about $2X10^{-4}$ in^2 to $5X10^{-2}$ in^2 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5200 and a tubular member during the radial expansion process.

In a preferred embodiment, the expansion cone 5200 includes a plurality of axial grooves 5220 coupled to each of the circumferential grooves 5215. In a preferred embodiment, the cross sectional area of the axial grooves 5220 ranges from about $2X10^{-4}$ in^2 to $5X10^{-2}$ in^2 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5200 and a tubular member during the radial expansion process. In a preferred embodiment, the cross sectional area of the circumferential grooves 5215 is greater than the cross sectional area of the axial grooves 5220 in order to minimize resistance to fluid flow. In a preferred embodiment, the axial groves 5220 are spaced apart in the circumferential direction by at least about 3 inches in order to optimally provide lubrication during the radial expansion process.

Referring to Fig. 11, another embodiment of a system for lubricating the interface between an expansion cone and a tubular member during the expansion process will now be described. As illustrated in Fig. 11, an expansion cone 5300, having a front end 5300a and a rear end 5300b, includes a tapered portion 5305 having an outer surface 5310, one or more circumferential grooves 5315a and 5315b, and one or more internal flow passages 5320a and 5320b.

In a preferred embodiment, the circumferential grooves 5315 are fluidicly coupled to the internal flow passages 5320. In this manner, during the radial expansion process, lubricating fluids are transmitted from the areas in front of the front 5300a and/or behind the rear 5300b of the expansion cone 5300 into the circumferential grooves 5315. Thus, the trailing edge portion of the interface between the expansion cone 5300 and a tubular member is provided with an increased supply of lubricant, thereby reducing the amount of force required to radially expand the

tubular member. Furthermore, the lubricating fluids also preferably pass to the area in front of the expansion cone. In this manner, the area adjacent to the front 5300a of the expansion cone 5300 is cleaned of foreign materials. In a preferred embodiment, the lubricating fluids are injected into the internal flow passages 5320 by pressurizing the area behind the rear 5300b of the expansion cone 5300 during the radial expansion process.

In a preferred embodiment, the expansion cone 5300 includes a plurality of circumferential grooves 5315. In a preferred embodiment, the cross sectional area of the circumferential grooves 5315 ranges from about $2X10^{-4}$ in^2 to $5X10^{-2}$ in^2 respectively, in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5300 and a tubular member during the radial expansion process. In a preferred embodiment, the expansion cone 5300 includes circumferential grooves 5315 that are concentrated about the axial midpoint of the tapered portion 5305 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5300 and a tubular member during the radial expansion process. In a preferred embodiment, the circumferential grooves 5315 are equally spaced along the trailing edge portion of the expansion cone 5300 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5300 and a tubular member during the radial expansion process.

In a preferred embodiment, the expansion cone 5300 includes a plurality of flow passages 5320 coupled to each of the circumferential grooves 5315. In a preferred embodiment, the flow passages 5320 fluidicly couple the front end 5300a and the rear end 5300b of the expansion cone 5300. In a preferred embodiment, the cross-sectional area of the flow passages 5320 ranges from about $2X10^{-4}$ in^2 to $5X10^{-2}$ in^2 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5300 and a tubular member during the radial expansion process. In a preferred embodiment, the cross sectional area of the circumferential grooves 5315 is greater than the cross-sectional area of the flow passages 5320 in order to minimize resistance to fluid flow.

Referring to Fig. 12, an embodiment of a system for lubricating the interface between an expansion cone and a tubular member during the expansion process will now be described. As illustrated in Fig. 12, an expansion cone 5400, having a front end 5400a and a rear end 5400b, includes a tapered portion 5405 having an outer surface 5410, one or more circumferential grooves 5415a and 5415b, and one or more axial grooves 5420a and 5420b.

In a preferred embodiment, the circumferential grooves 5415 are fluidicly coupled to the axial grooves 5420. In this manner, during the radial expansion process, lubricating fluids are transmitted from the areas in front of the front 5400a and/or behind the rear 5400b of the expansion cone 5400 into the circumferential grooves 5415. Thus, the trailing edge portion of the interface between the expansion cone 5400 and a tubular member is provided with an increased supply of lubricant, thereby reducing the amount of force required to radially expand the tubular member. Furthermore, in a preferred embodiment, pressurized lubricating fluids pass from the fluid passages 5420 to the area in front of the front 5400a of the expansion cone 5400. In this manner, the area adjacent to the front 5400a of the expansion cone 5400 is cleaned of foreign materials. In a preferred embodiment, the lubricating fluids are injected into the internal flow passages 5420 by pressurizing the area behind the rear 5400b expansion cone 5400 during the radial expansion process.

In a preferred embodiment, the expansion cone 5400 includes a plurality of circumferential grooves 5415. In a preferred embodiment, the cross sectional area of the circumferential grooves 5415 range from about $2X10^{-4}$ in^2 to $5X10^{-2}$ in^2 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5400 and a tubular member during the radial expansion process. In a preferred embodiment, the expansion cone 5400 includes circumferential grooves 5415 that are concentrated about the axial midpoint of the tapered portion 5405 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5400 and a tubular member during the radial expansion process. In a preferred embodiment, the circumferential grooves 5415 are equally spaced along the trailing edge portion of the expansion cone 5400 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5400 and a tubular member during the radial expansion process.

In a preferred embodiment, the expansion cone 5400 includes a plurality of axial grooves 5420 coupled to each of the circumferential grooves 5415. In a preferred embodiment, the axial grooves 5420 fluidicly couple the front end and the rear end of the expansion cone 5400. In a preferred embodiment, the cross sectional area of the axial grooves 5420 range from about $2X10^{-4}$ in^2 to $5X10^{-2}$ in^2, respectively, in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5400 and a tubular member during the radial expansion process. In a preferred embodiment, the cross sectional area of the circumferential grooves 5415 is greater than the cross sectional area of the axial grooves 5420 in order to minimize resistance to fluid flow. In a preferred embodiment, the axial grooves 5420 are spaced

apart in the circumferential direction by at least about 3 inches in order to optimally provide lubrication during the radial expansion process.

Referring to Fig. 13, another embodiment of a system for lubricating the interface between an expansion cone and a tubular member during the expansion process will now be described. As illustrated in Fig. 13, an expansion cone 5500, having a front end 5500a and a rear end 5500b, includes a tapered portion 5505 having an outer surface 5510, one or more circumferential grooves 5515a and 5515b, and one or more axial grooves 5520a and 5520b.

In a preferred embodiment, the circumferential grooves 5515 are fluidicly coupled to the axial grooves 5520. In this manner, during the radial expansion process, lubricating fluids are transmitted from the area ahead of the front 5500a of the expansion cone 5500 into the circumferential grooves 5515. Thus, the trailing edge portion of the interface between the expansion cone 5500 and a tubular member is provided with an increased supply of lubricant, thereby reducing the amount of force required to radially expand the tubular member. In a preferred embodiment, the lubricating fluids are injected into the axial grooves 5520 using a fluid conduit that is coupled to the tapered end 3205 of the expansion cone 3200.

In a preferred embodiment, the expansion cone 5500 includes a plurality of circumferential grooves 5515. In a preferred embodiment, the cross sectional area of the circumferential grooves 5515 ranges from about $2X10^{-4}$ in^2 to $5X10^{-2}$ in^2 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5500 and a tubular member during the radial expansion process. In a preferred embodiment, the expansion cone 5500 includes circumferential grooves 5515 that are concentrated about the axial midpoint of the tapered portion 5505 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5500 and a tubular member during the radial expansion process. In a preferred embodiment, the circumferential grooves 5515 are equally spaced along the trailing edge portion of the expansion cone 5500 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5500 and a tubular member during the radial expansion process.

In a preferred embodiment, the expansion cone 5500 includes a plurality of axial grooves 5520 coupled to each of the circumferential grooves 5515. In a preferred embodiment, the axial grooves 5520 intersect each of the circumferential groves 5515 at an acute angle. In a preferred embodiment, the cross sectional area of the axial grooves 5520 ranges from about $2X10^{-4}$ in^2 to $5X10^{-2}$ in^2 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone

5500 and a tubular member during the radial expansion process. In a preferred embodiment, the cross sectional area of the circumferential grooves 5515 is greater than the cross sectional area of the axial grooves 5520. In a preferred embodiment, the axial grooves 5520 are spaced apart in the circumferential direction by at least about 3 inches in order to optimally provide lubrication during the radial expansion process. In a preferred embodiment, the axial grooves 5520 intersect the longitudinal axis of the expansion cone 5500 at a larger angle than the angle of attack of the tapered portion 5505 in order to optimally provide lubrication during the radial expansion process.

Referring to Fig. 14, another embodiment of a system for lubricating the interface between an expansion cone and a tubular member during the expansion process will now be described. As illustrated in Fig. 14, an expansion cone 5600, having a front end 5600a and a rear end 5600b, includes a tapered portion 5605 having an outer surface 5610, a spiral circumferential groove 5615, and one or more internal flow passages 5620.

In a preferred embodiment, the circumferential groove 5615 is fluidicly coupled to the internal flow passage 5620. In this manner, during the radial expansion process, lubricating fluids are transmitted from the area ahead of the front 5600a of the expansion cone 5600 into the circumferential groove 5615. Thus, the trailing edge portion of the interface between the expansion cone 5600 and a tubular member is provided with an increased supply of lubricant, thereby reducing the amount of force required to radially expand the tubular member. In a preferred embodiment, the lubricating fluids are injected into the internal flow passage 5620 using a fluid conduit that is coupled to the tapered end 5605 of the expansion cone 5600.

In a preferred embodiment, the expansion cone 5600 includes a plurality of spiral circumferential grooves 5615. In a preferred embodiment, the cross sectional area of the circumferential groove 5615 ranges from about $2X10^{-4}$ in^2 to $5X10^{-2}$ in^2 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5600 and a tubular member during the radial expansion process. In a preferred embodiment, the expansion cone 5600 includes circumferential grooves 5615 that are concentrated about the axial midpoint of the tapered portion 5605 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5600 and a tubular member during the radial expansion process. In a preferred embodiment, the circumferential grooves 5615 are equally spaced along the trailing edge portion of the expansion cone 5600 in order to optimally

provide lubrication to the trailing edge portion of the interface between the expansion cone 5600 and a tubular member during the radial expansion process.

In a preferred embodiment, the expansion cone 5600 includes a plurality of flow passages 5620 coupled to each of the circumferential grooves 5615. In a preferred embodiment, the cross-sectional area of the flow passages 5620 ranges from about $2X10^{-4}$ in^2 to $5X10^{-2}$ in^2 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5600 and a tubular member during the radial expansion process. In a preferred embodiment, the cross sectional area of the circumferential groove 5615 is greater than the cross sectional area of the flow passage 5620 in order to minimize resistance to fluid flow.

Referring to Fig. 15, another embodiment of a system for lubricating the interface between an expansion cone and a tubular member during the expansion process will now be described. As illustrated in Fig. 15, an expansion cone 5700, having a front end 5700a and a rear end 5700b, includes a tapered portion 5705 having an outer surface 5710, a spiral circumferential groove 5715, and one or more axial grooves 5720a, 5720b and 5720c.

In a preferred embodiment, the circumferential groove 5715 is fluidicly coupled to the axial grooves 5720. In this manner, during the radial expansion process, lubricating fluids are transmitted from the area ahead of the front 5700a of the expansion cone 5700 into the circumferential groove 5715. Thus, the trailing edge portion of the interface between the expansion cone 5700 and a tubular member is provided with an increased supply of lubricant, thereby reducing the amount of force required to radially expand the tubular member. In a preferred embodiment, the lubricating fluids are injected into the axial grooves 5720 using a fluid conduit that is coupled to the tapered end 5705 of the expansion cone 5700.

In a preferred embodiment, the expansion cone 5700 includes a plurality of spiral circumferential grooves 5715. In a preferred embodiment, the cross sectional area of the circumferential grooves 5715 range from about $2X10^{-4}$ in^2 to $5X10^{-2}$ in^2 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5700 and a tubular member during the radial expansion process. In a preferred embodiment, the expansion cone 5700 includes circumferential grooves 5715 concentrated about the axial midpoint of the tapered portion 5705 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5700 and a tubular member during the radial expansion process. In a preferred embodiment, the circumferential grooves 5715 are equally spaced along the trailing edge portion of the expansion cone 5700 in order to optimally

provide lubrication to the trailing edge portion of the interface between the expansion cone 5700 and a tubular member during the radial expansion process.

In a preferred embodiment, the expansion cone 5700 includes a plurality of axial grooves 5720 coupled to each of the circumferential grooves 5715. In a preferred embodiment, the cross sectional area of the axial grooves 5720 range from about $2X10^{-4}$ in^2 to $5X10^{-2}$ in^2 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5700 and a tubular member during the radial expansion process. In a preferred embodiment, the axial grooves 5720 intersect the circumferential grooves 5715 in a perpendicular manner. In a preferred embodiment, the cross sectional area of the circumferential groove 5715 is greater than the cross sectional area of the axial grooves 5720 in order to minimize resistance to fluid flow. In a preferred embodiment, the circumferential spacing of the axial grooves is greater than about 3 inches in order to optimally provide lubrication during the radial expansion process. In a preferred embodiment, the axial grooves 5720 intersect the longitudinal axis of the expansion cone at an angle greater than the angle of attack of the tapered portion 5705 in order to optimally provide lubrication during the radial expansion process.

Referring to Fig. 16, a preferred embodiment of a system for lubricating the interface between an expansion cone and a tubular member during the expansion process will now be described. As illustrated in Fig. 16, an expansion cone 5800, having a front end 5800a and a rear end 5800b, includes a tapered portion 5805 having an outer surface 5810, a circumferential groove 5815, a first axial groove 5820, and one or more second axial grooves 5825a, 5825b, 5825c and 5825d.

In a preferred embodiment, the circumferential groove 5815 is fluidicly coupled to the axial grooves 5820 and 5825. In this manner, during the radial expansion process, lubricating fluids are preferably transmitted from the area behind the back 5800b of the expansion cone 5800 into the circumferential groove 5815. Thus, the trailing edge portion of the interface between the expansion cone 5800 and a tubular member is provided with an increased supply of lubricant, thereby reducing the amount of force required to radially expand the tubular member. In a preferred embodiment, the lubricating fluids are injected into the first axial groove 5820 by pressurizing the region behind the back 5800b of the expansion cone 5800. In a preferred embodiment, the lubricant is further transmitted into the second axial grooves 5825 where the lubricant preferably cleans foreign materials from the tapered portion 5805 of the expansion cone 5800.

In a preferred embodiment, the expansion cone 5800 includes a plurality of circumferential grooves 5815. In a preferred embodiment, the cross sectional area of the circumferential groove 5815 ranges from about $2X10^{-4}$ in^2 to $5X10^{-2}$ in^2 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5800 and a tubular member during the radial expansion process. In a preferred embodiment, the expansion cone 5800 includes circumferential grooves 5815 concentrated about the axial midpoint of the tapered portion 5805 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5800 and a tubular member during the radial expansion process. In a preferred embodiment, the circumferential grooves 5815 are equally spaced along the trailing edge portion of the expansion cone 5800 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5800 and a tubular member during the radial expansion process.

In a preferred embodiment, the expansion cone 5800 includes a plurality of first axial grooves 5820 coupled to each of the circumferential grooves 5815. In a preferred embodiment, the first axial grooves 5820 extend from the back 5800b of the expansion cone 5800 and intersect the circumferential groove 5815. In a preferred embodiment, the cross sectional area of the first axial groove 5820 ranges from about $2X10^{-4}$ in^2 to $5X10^{-2}$ in^2 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5800 and a tubular member during the radial expansion process. In a preferred embodiment, the first axial groove 5820 intersects the circumferential groove 5815 in a perpendicular manner. In a preferred embodiment, the cross sectional area of the circumferential groove 5815 is greater than the cross sectional area of the first axial groove 5820 in order to minimize resistance to fluid flow. In a preferred embodiment, the circumferential spacing of the first axial grooves 5820 is greater than about 3 inches in order to optimally provide lubrication during the radial expansion process.

In a preferred embodiment, the expansion cone 5800 includes a plurality of second axial grooves 5825 coupled to each of the circumferential grooves 5815. In a preferred embodiment, the second axial grooves 5825 extend from the front 5800a of the expansion cone 5800 and intersect the circumferential groove 5815. In a preferred embodiment, the cross sectional area of the second axial grooves 5825 ranges from about $2X10^{-4}$ in^2 to $5X10^{-2}$ in^2 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5800 and a tubular member during the radial expansion process. In a preferred embodiment, the second axial grooves 5825 intersect the circumferential groove 5815 in a perpendicular manner. In

a preferred embodiment, the cross sectional area of the circumferential groove 5815 is greater than the cross sectional area of the second axial grooves 5825 in order to minimize resistance to fluid flow. In a preferred embodiment, the circumferential spacing of the second axial grooves 5825 is greater than about 3 inches in order to optimally provide lubrication during the radial expansion process. In a preferred embodiment, the second axial grooves 5825 intersect the longitudinal axis of the expansion cone 5800 at an angle greater than the angle of attack of the tapered portion 5805 in order to optimally provide lubrication during the radial expansion process.

Referring to Fig. 17, in a preferred embodiment, the first axial groove 5820 includes a first portion 5905 having a first radius of curvature 5910, a second portion 5915 having a second radius of curvature 5920, and a third portion 5925 having a third radius of curvature 5930. In a preferred embodiment, the radius of curvatures, 5910, 5920 and 5930 are substantially equal. In an exemplary embodiment, the radius of curvatures, 5910, 5920 and 5930 are all substantially equal to 0.0625 inches.

Referring to Fig. 18, in a preferred embodiment, the circumferential groove 5815 includes a first portion 6005 having a first radius of curvature 6010, a second portion 6015 having a second radius of curvature 6020, and a third portion 6025 having a third radius of curvature 6030. In a preferred embodiment, the radius of curvatures, 6010, 6020 and 6030 are substantially equal. In an exemplary embodiment, the radius of curvatures, 6010, 6020 and 6030 are all substantially equal to 0.125 inches.

Referring to Fig. 19, in a preferred embodiment, the second axial groove 5825 includes a first portion 6105 having a first radius of curvature 6110, a second portion 6115 having a second radius of curvature 6120, and a third portion 6125 having a third radius of curvature 6130. In a preferred embodiment, the first radius of curvature 6110 is greater than the third radius of curvature 6130. In an exemplary embodiment, the first radius of curvature 6110 is equal to 0.5 inches, the second radius of curvature 6120 is equal to 0.0625 inches, and the third radius of curvature 6130 is equal to 0.125 inches.

Referring to Fig. 20, an embodiment of an expansion mandrel 6200 includes an internal flow passage 6205 having an insert 6210 including a flow passage 6215. In a preferred embodiment, the cross sectional area of the flow passage 6215 is less than the cross sectional area of the flow passage 6215. More generally, in a preferred embodiment, a plurality of inserts 6210 are provided, each with different sizes of flow passages 6215. In this manner, the flow passage 6215 is machined to a standard size, and the lubricant supply is varied by using different sized inserts 6210. In a preferred

embodiment, the teachings of the expansion mandrel 6200 are incorporated into the expansion mandrels 5100, 5300, and 5600.

Referring to Fig. 21, in a preferred embodiment, the insert 6210 includes a filter 6305 for filtering particles and other foreign materials from the lubricant that passes into the flow passage 6205. In this manner, the foreign materials are prevented from clogging the flow passage 6205 and other flow passages within the expansion mandrel 6200.

In a preferred embodiment, the one or more of the lubrication systems and elements of the mandrels 5100, 5200, 5300, 5400, 5500, 5600, 5700, 5800 and/or 5900 are incorporated into the methods and apparatus for expanding tubular members described above with reference to Figs. 1-7. In this manner, the amount of force required to radially expand a tubular member in the formation and/or repair of a wellbore casing, pipeline, or structural support is significantly reduced. Furthermore, the increased lubrication provided to the trail edge portion of the mandrel greatly reduces the amount of galling or seizure caused by the interface between the mandrel and the tubular member during the radial expansion process thereby permitting larger continuous sections of tubulars to be radially expanded in a single continuous operation. Thus, use of the mandrels 5100, 5200, 5300, 5400, 5500, 5600, 5700, 5800 and/or 5900 reduces the operating pressures required for radial expansion and thereby reduces the sizes of the required hydraulic pumps and related equipment. In addition, failure, bursting, and/or buckling of tubular members during the radial expansion process is significantly reduced, and the success ratio of the radial expansion process is greatly increased.

In laboratory tests, a regular expansion cone, without any lubrication grooves and flow passages, and the expansion cone 5100 were both used to radially expand identical coiled tubular members, each having an outside diameter of 3 ½ inches. The following tables summarizes the results of this laboratory test:

LUBRICATING FLUID	REGULAR EXPANSION CONE	EXPANSION CONE 5100
	FORCE REQUIRED TO EXPAND TUBULAR MEMBER	
PHPA Mud alone	78,000 lbf	72,000 lbf
PHPA Mud + 7%	48,000 lbf	46,000 lbf

Lubricant Blend		
100% Lubricant Blend	68,000 lbf	48,000 lbf

Where:PHPA Mud refers to a drilling mud mixture available from Baroid.

PHPA Mud + 7 % Lubricant Blend refers to a mixture of 93% PHPA Mud and 7% mixture of TorqTrim III, EP Mudlib, and DrillN-Slid available from Baroid.

100% Lubricant Blend refers to a mixture of TorqTrim III, EP Mudlib, and DrillN-Slid available from Baroid.

Thus, in an exemplary embodiment, the use of the expansion cone 5100 reduced the amount of force required to radially expand a tubular member by as much as 30%. This reduction in the required force translates to a corresponding reduction in the overall energy requirements as well as a reduction in the size of required operating equipment such as, for example, hydraulic pumping equipment. During the course of a typical expansion operation, this results in tremendous cost savings to the operator.

In a preferred embodiment, the lubricating fluids used with the mandrels 5100, 5200, 5300, 5400, 5500, 5600, 5700, 5800 and 5900 for expanding tubular members have viscosities ranging from about 1 to 10,000 centipoise in order to optimize the injection of the lubricating fluids into the circumferential grooves of the mandrels during the radial expansion process.

In a preferred embodiment, prior to placement in a wellbore, the outer surfaces of the apparatus for expanding tubular members described above with reference to Figs. 1-7 are coated with a lubricating fluid to facilitate their placement the wellbore and reduce surge pressures. In a preferred embodiment, the lubricating fluid comprises BARO-LUB GOLD-SEAL™ brand drilling mud lubricant, available from Baroid Drilling Fluids, Inc. In this manner, the insertion of the apparatus into a wellbore, pipeline or other opening is optimized.

Referring to Fig. 22, a preferred embodiment of an expandable tubular 6400 for use in forming and/or repairing a wellbore casing, pipeline, or foundation support will now be described. In a preferred embodiment, the expandable tubular 6400 includes a wall thickness T.

In a preferred embodiment, the wall thickness T is substantially constant throughout the expandable tubular 6400. In a preferred embodiment, the variation in the wall thickness T about the circumference of the tubular member 6400 is less than about 8 % in order to optimally provide an expandable tubular 6400 having a substantially constant hoop yield strength.

In a preferred embodiment, the material composition of and the manufacturing processes used in forming the expandable tubular 6400 are selected to provide a hoop yield strength that varies less than about 10 % about the circumference of the tubular member 6400 in order to optimally provide consistent geometries in the expandable tubular 6400 after radial expansion.

In a preferred embodiment, the expandable tubular 6400 includes structural imperfections such as, for example, voids, foreign material, cracks, of less than about 5 % of the specified wall thickness T in order to optimize the radial expansion of the expandable tubular member 6400. In a preferred embodiment, each expandable tubular 6400 is tested for the presence of such defects using nondestructive testing methods in accordance with industry standard API SR2.

Referring to Fig. 23, a preferred embodiment of an expansion cone 6700 for radially expanding the tubular member 6500 will now be described. The expansion cone 6700 preferably includes a front end 6705, a rear end 6710, and a radial expansion section 6715. In a preferred embodiment, the expansion cone 6700 is used in one or more the embodiments of apparatus and methods for radially expanding a tubular member described above with reference to Figs. 1-22. In a preferred embodiment, when the expansion cone 6700 is displaced in the longitudinal direction relative to the tubular member 6500, the interaction of the exterior surface of the radial expansion section 6715 with the interior surface of the tubular member 6500 causes the tubular member 6500 to expand in the radial direction.

The radial expansion section 6715 preferably includes a first conical outer surface 6720 and a second conical outer surface 6725. The first conical outer surface 6720 includes an angle of attack α_1 and the second conical outer surface 6725 includes an angle of attack α_2. In a preferred embodiment, the angle of attack α_1 is greater than the angle of attack α_2. In this manner, the first conical outer surface 6720 optimally radially overexpands the intermediate portion 6530 of the tubular member 6500 and the second conical outer surface 6725 optimally radially overexpands the pre-expanded first and second ends, 6520 and 6535, of the tubular member 6500. In a preferred embodiment, the first conical outer surface 6720 includes an angle of attack α_1 ranging from about 8 to 20 degrees. In a preferred embodiment, the second conical outer

surface 6725 includes an angle of attack α_2 ranging from about 4 to 15 degrees. More generally, the expansion cone 6700 may include 3 or more adjacent conical outer surfaces having angles of attack that decrease from the front end 6705 of the expansion cone 6700 to the rear end 6710 of the expansion cone 6700.

Referring to Fig. 24, an alternative preferred embodiment of an expansion cone 6800 for radially expanding the tubular member 6500 will now be described. The expansion cone 6800 preferably includes a front end 6805, a rear end 6810, and a radial expansion section 6815. In a preferred embodiment, the expansion cone 6800 is used in one or more the embodiments of apparatus and methods for radially expanding a tubular member described above with reference to Figs. 1-22. In a preferred embodiment, when the expansion cone 6800 is displaced in the longitudinal direction relative to the tubular member 6500, the interaction of the exterior surface of the radial expansion section 6815 with the interior surface of the tubular member 6500 causes the tubular member 6500 to expand in the radial direction.

The radial expansion section 6815 preferably includes an outer surface 6820 having a substantially parabolic outer profile. In this manner, the outer surface 6820 provides an angle of attack that constantly decreases from a maximum at the front end 6805 of the expansion cone 6800 to a minimum at the rear end 6810 of the expansion cone. The parabolic outer profile of the outer surface 6820 may be formed using a plurality of adjacent discrete conical sections and/or using a continuous curved surface. In this manner, the area of the outer surface 6820 adjacent to the front end 6805 of the expansion cone 6800 optimally radially overexpands the intermediate portion 6530 of the tubular member 6500, while the area of the outer surface 6820 adjacent to the rear end 6810 of the expansion cone 6800 optimally radially overexpands the pre-expanded first and second ends, 6520 and 6535, of the tubular member 6500. In a preferred embodiment, the parabolic profile of the outer surface 6820 is selected to provide an angle of attack that ranges from about 8 to 20 degrees in the vicinity of the front end 6805 of the expansion cone 6800 and an angle of attack in the vicinity of the rear end 6810 of the expansion cone 6800 from about 4 to 15 degrees.

Although illustrative embodiments of the invention have been shown and described, a wide range of modification, changes and substitution is contemplated in the foregoing disclosure. In some instances, some features of the present invention may be employed without a corresponding use of the other features. Accordingly, it is appropriate that the appended claims be construed broadly and in a manner consistent with the scope of the invention.

CLAIMS

1. An expansion cone for radially expanding a round tubular member in a wellbore from a first radial size to a second larger radial size, comprising:

an expansion cone body comprising a plurality of adjacent discrete tapered sections.

2. The expansion cone of claim 1, wherein the angle of attack of the adjacent discrete tapered sections increases in a continuous manner from one end of the expansion cone body to the opposite end of the expansion cone body.

3. The expansion cone of claim 1 or 2, wherein the plurality of adjacent discrete tapered sections comprises three or more adjacent discrete tapered sections.

4. The expansion cone of any one of claims 1 to 3, wherein the expansion cone comprises a front end and a back end.

5. The expansion cone of claim 4, wherein a tapered section adjacent the front end comprises an angle of attack of about 8 to 20 degrees

6. The expansion cone of claim 4 or 5, wherein a tapered section adjacent the back end comprises an angle of attack of about 4 to 15 degrees.

7. The expansion cone of any one of claims 4 to 6, wherein angles of attack of the adjacent discrete tapered sections decrease from the front end to the back end.

8. The expansion cone of any one of claims 4 to 7, wherein the plurality of adjacent discrete tapered sections comprises a first tapered section adjacent the front end and a second tapered section adjacent the back end, the first tapered section comprising an angle of attack of about 8 to 20 degrees, and the second tapered section comprising an angle of attack of about 4 to 15 degrees.

9. The expansion cone of any one of claims 1 to 8 wherein:

at least a portion of the expansion cone body has an angle of attack of 25°.

10. The expansion cone of any one of claims 1 to 9 further comprising:

a lubricant on an outer surface of the expansion cone body.

11. The expansion cone of any one of claims 1 to 10 further comprising:
one or more grooves formed in an outer surface of the expansion cone body.

12. The expansion cone of any one of claims 1 to 11 further comprising:
one or more axial flow passages defined within the paraboloid expansion cone body.

13. The expansion cone of claim 11, wherein the grooves comprise circumferential grooves.

14. The expansion cone of claim 11, wherein the grooves comprise spiral grooves.

15. The expansion cone of claim 11, 13, or 14, wherein the grooves are concentrated around an axial midpoint of the expansion cone body.

16. The expansion cone of claim 12, wherein the axial flow passages comprise axial grooves.

17. The expansion cone of claim 16, wherein the axial grooves are spaced apart by at least about 3 inches in the circumferential direction.

18. The expansion cone of any one of claims 1 to 11 or 13 to 15, further comprising one or more flow passages, wherein the flow passages are positioned within the expansion cone body.

19. The expansion cone of claim 18, wherein the flow passages are coupled to one or more grooves.

20. The expansion cone of claim 18 or 19, wherein one or more of the flow passages include inserts having restricted flow passages.

21. The expansion cone of any one of claims 18 to 20, wherein one or more of the flow passages include filters.

22. The expansion cone of any one of claims 11, 13 to 15, or 18 to 21, wherein the cross-sectional area of the grooves ranges from 1.29×10^{-7} m^2 to 3.226×10^{-5} m^2 (2×10^{-4} in^2 to 5×10^{-2} in^2).

23. The expansion cone of claim 12, 16, or 17, wherein the cross-sectional area of the axial flow passages ranges from about 1.29×10^{-7} m^2 to 3.226×10^{-5} m^2 (2×10^{-4} in^2 to 5×10^{-2} in^2).

24. The expansion cone of any one of claims 11, 13 to 15, or 18 to 22, wherein the grooves include:

a flow channel having a first radius of curvature;

a first shoulder positioned on one side of the flow channel having a second radius of curvature; and

a second shoulder positioned on the other side of the flow channel having a third radius of curvature.

25. The expansion cone of claim 24, wherein the first, second and third radii of curvature are substantially equal.

26. The expansion cone of claim 12, 16, 17, or 23, wherein the axial flow passages include:

a flow channel having a first radius of curvature;

a first shoulder positioned on one side of the flow channel having a second radius of curvature; and

a second shoulder positioned on the other side of the flow channel having a third radius of curvature.

27. The expansion cone of claim 26, wherein the first, second and third radii of curvature are substantially equal.

28. The expansion cone of claim 26, wherein the second radius of curvature is greater than the third radius of curvature.